U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-295 055

Evaluation of Particulate Mass Monitors Using the Beta Gauge Technique

Particle Data Labs Ltd, Elmhurst, IL

Prepared for

Environmental Sciences Research Lab, Research Triangle Park, NC Emissions Measurement and Characterization Div

Apr 79

United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

EPA-600/2-79-073
April 1979

Research and Development

PB 295055

EPA

Evaluation of Particulate Mass Monitors Using the Beta Gauge Technique

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-79-073	2.
3. RECIPIENT'S ACCESSION NO. PB295055	
4. TITLE AND SUBTITLE EVALUATION OF PARTICULATE MASS MONITORS USING THE BETA GAUGE TECHNIQUE	5. REPORT DATE April 1979 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Meryl R. Jackson	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Particle Data Laboratories, Ltd. Elmhurst, Illinois 60126	10. PROGRAM ELEMENT NO. 1A1010 26AAM64 (FY-73) 11. CONTRACT/GRANT NO. 68-02-1216
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, N. C. 27711	13. TYPE OF REPORT AND PERIOD COVERED Final 6/73 - 2/75 14. SPONSORING AGENCY CODE EPA/600/9
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

A field study was conducted to evaluate two commercially available beta gauge instruments for measuring particulate mass concentrations in stationary source emissions. Performance of the instruments was compared with a manual method of measurement at a ferrite rotary-kiln calciner, at a slurry cement kiln with an electrostatic precipitator, and at an oil-fired boiler.

Tests were conducted over a 168-hour period to establish instrument accuracy, calibration error, drift and system reliability. Descriptions of the instruments, test programs and test sites are presented together with a detailed summary of the experimental data.

The accuracy of the beta gauge instruments was strongly dependent upon the sampling characteristics of the extractive probes. The instruments tested were not capable of correctly measuring the particulate concentration in the stack, nor of operating continuously for a 168-hour period. In the case of the cement kiln, the particle concentration measured by the beta gauge instruments correlated well with the concentration determined from the filter catch portion of the manual method, but not with the fiber plus probe catch.

Particle deposition in the probe of the beta instruments was as high as 86% (average) for the cement plant emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
* Air pollution * Particles * Mass * Measurement * Beta particles Evaluation Field tests		13B 20H 14B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED 20. SECURITY CLASS *(This page)* UNCLASSIFIED	21. NO. OF PAGES 73 22. PRICE A04-A01

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

EPA-600/2-79-073
April 1979

EVALUATION OF PARTICULATE MASS MONITORS USING THE BETA GAUGE TECHNIQUE

by

Meryl R. Jackson
Particle Data Laboratories, Ltd.
Elmhurst, Illinois 60126

Contract No. 68-02-1216

Project Officer

John Nader
Emission Measurements and Characterization Division
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

ia

DISCLAIMER

This report has been reviewed by the Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

A field study was conducted to evaluate two commercially available beta gauge instruments for measuring particulate mass concentrations in stationary source emissions. Performance of the instruments was compared with a manual method of measurement at a ferrite rotary-kiln calciner, at a slurry cement kiln with an electrostatic precipitator, and at an oil-fired boiler.

Tests were conducted over a 168-hour period to establish instrument accuracy, calibration error, drift, and system reliability. Descriptions of the instruments, test programs and test sites are presented together with a detailed summary of the experimental data.

The accuracy of the beta gauge instruments was strongly dependent upon the sampling characteristics of the extractive probes. The instruments tested were not capable of correctly measuring the particulate concentration in the stack, nor of operating continuously for a 168-hour period. In the case of the cement kiln, the particle concentration measured by the beta gauge instruments correlated well with the concentration determined from the filter catch portion of the manual method, but not with the fiber plus probe catch.

Particle deposition in the probe of the beta instruments was as high as 86% (average) for the cement plant emissions.

CONTENTS

Abstract		iii
Figures		vi
Tables		vii
Acknowledgments		viii
1.	Introduction	1
2.	Conclusions	2
3.	Recommendations	3
4.	Site Descriptions	4
5.	Instrument Descriptions	6
6.	Text Program	8
7.	Field Experience	12
8.	Calibration Checks of Beta Gauges	16
9.	Results	17
10.	Discussion	36
References		39
Appendices		40
A.	Instrument Design and Operation - Argos 1	41
B.	Instrument Design and Operation - Model 2414	51
C.	Description of the Particulate Reference Method Using the EPA Sampling Train	56
D.	Statistical Analysis	62

FIGURES

Number		Page
1	Point Location	10
2	Filter Catch Only as Reference, LSI Instrument - Site 1	25
3	Filter Catch Plus Probe Washing As Reference, LSI Instrument - Site 1	26
4	Filter Catch Only as Reference, LSI Instrument - Site 2	27
5	Filter Catch Plus Probe Washing as Reference, LSI Instrument - Site 2	28
6	Filter Catch Only as Reference, RAC Instrument - Site 2	29
7	Filter Catch Plus Probe Washing, RAC Instrument - Site 2	30
8	Filter Catch Only as Reference, LSI Instrument - Site 3	31
9	Filter Catch Plus Probe Washing as Reference, LSI Instrument - Site 3	32
10	Filter Catch Only as Reference, RAC Instrument - Site 3	33
11	Filter Catch Plus Probe Washing, RAC Instrument - Site 3	34

TABLES

Number		Page
1	Test Program - Site 1	9
2	Program Test Conditions - Site 1	11
3A	Site 1 - Data for L.S.I. - Observations with Filter Catch Only as Reference	18
3B	Site 1 - Data for L.S.I. - Observations Using Filter Catch Plus Probe Washings as Reference	19
4A	Site 2 - Data for RAC and L.S.I. - Observations with Filter Catch Only as Reference	20
4B	Site 2 - Data for RAC and L.S.I. - Observations with Filter Catch Plus Probe Washings as Reference	21
5A	Site 3 - Data for RAC and L.S.I. - Observations with Filter Catch Only as Reference	22
5B	Site 3 - Data for RAC and L.S.I. - Observations Using Filter Catch Plus Probe Washings as Reference	23
6	Regression Analysis of Data	24
7	Material Masses Deposited in the Probe System	35
8	Absolute Mean Value Plus 95% Confidence	37
9	Absolute Mean Value Plus 95% Confidence	37
10	Instantaneous Drift Using Linear Interpolation	38

ACKNOWLEDGMENTS

The support of Lear Siegler Inc. and Research Appliance Corporation in their extensive technical support of the testing program is gratefully acknowledged. Our thanks are also due for the services, assistance and hospitality extended to us at each of the three testing sites. We hope the information gained by our hosts to some extent off-sets their efforts on our behalf.

SECTION 1

INTRODUCTION

Present methods recommended by EPA for measurement of stack particulate loading are manual and provide information averaged over a minimum period of two hours. Particulate code compliance of any stationary emission source or performance evaluation of any control equipment is judged upon the results of three tests of between two to four hours duration performed within a one or two day period. A need exists for an automatic and more or less continuous measurement system of particulate emission rate from stationary sources similar to those presently available for measurement of sulfur dioxide and nitrogen oxides.

This report presents the result of an experimental study of the performance of two commercially available automatic and more or less continuous particulate mass monitoring systems. The major criteria of performance was measurement accuracy relative to the EPA manual test method, and reliability of unattended instrument operation over a 168 hour period.

Three test sites were selected for simultaneous measurement of particulate loading by the one manual and two automatic systems. The sites were selected to provide different effluent characteristics with respect to particle physical properties, effluent gas concentration, and particulate emission rates.

The data are presented and evaluated to provide assistance in the formulation of emission monitoring requirements, to furnish manufacturers with technical guidelines on the present and desired performance characteristics, and to inform potential users of automated particulate monitoring equipment capabilities.

SECTION 2

CONCLUSIONS

Two commercially available beta gauge methods for measurement of stack gas particulate loading concentrations were inaccurate in their measurement of total dust loading concentrations.

Both instruments had repeated mechanical and electronic failures indicating poor reliability and impacting on accuracy of measurements.

The degree of inaccuracy was affected largely by removal of particulate by deposition in the extractive probes before reaching the measurement system.

The investigation showed that the particulate concentrations as measured by the beta gauges bear no significant statistical correlation to the measurements obtained by the manual test method for the ferrite calciner or the oil fired boiler.

In the case of the cement kiln effluent the beta gauge measurements correlated well with the filter catch of the manual method.

Neither beta gauge instrument operated continuously for 168 hours without failure at any of the three sites tested.

SECTION 3

RECOMMENDATIONS

The physical principles involved in the measurement of mass by beta attenuation are well established and do provide a potential means of automatic mass concentration measurement. The instruments tested do not perform as intended mainly due to deficiencies in the interface between the stack gas and the filter tape. If adequate transportation of particles from the stack gas to the filter can be achieved, the system concept would appear to be viable.

It is therefore recommended that research and development effort be expended in correcting the deficiencies of the sampling interface. It is suggested that an alternative approach to previous effort in this area is to provide a filter transport system so that the particulates are collected on the filter at the sampling nozzle in the stack, and are transported to the measurement system as a filter deposit rather than as an aerosol.

SECTION 4

SITE DESCRIPTIONS

The following three sites were selected for performing the tests:

SITE 1

The stack selected for testing of instruments at the first site was a natural draft stack venting a gas fired hard ferrite rotary calcining kiln, approximately 9 meters long and 1.3 meters diameter. A raw material slurry mixture comprising a finely divided metal oxide and other salts suspension in water was sprayed into the upper end of the calciner. The calciner operating temperature was near 1300°C. Convective cooling and dilution air reduced the gas temperatures in the stack generally to the range 260°C to 370°C.

The stack effluent contained approximately 18% moisture and two components of particulate material. One component appeared as a submicron fumed material, while the other was apparently red iron oxide in the 10 micrometer and larger size range. Gas analysis indicated that the CO_2 and O_2 concentrations of 4.6% and 14.0% respectively were governed only by the natural gas combustion heating in the calciner.

The stack comprised a nominal 60 cm diameter vertical steel tube approximately 13.6 meters in height and capped with a rotating cowl. The calciner breeching entered the stack at a height of approximately 4.6 meters. The sampling plane was located at approximately 6 meters above the breeching and 3 meters below the top of the stack.

Under normal operation the calciner was fed with slurry 24 hours a day, 5 days a week, alternately from one of two slurry tanks. At the week-ends the slurry feed was stopped, and the calciner temperature reduced to 870°C. At approximately four hour intervals during operation, the natural gas and slurry feeds were stopped while the fire ring was removed by rodding and the gas flame photoelectric cell sight tube was cleaned. The slurry feed was stopped for approximately 5 to 10 minutes during this process.

SITE 2

A wet slurry cement kiln exhaust was selected as the second testing site. Sampling was performed in the near-vertical duct between the electrostatic precipitator and the ID fan prior to exhausting to the stack. At the testing location the gas was flowing vertically downward through a rectangular cross sectional duct 2.14 meters x 1.27 meters. The average gas temperature was 175°C., gas moisture was approximately 33%, and CO_2 and O_2 concentrations were near 8% and 11% respectively. The average particle size of the collected particles was approximately 25 micrometers, but the size distribution extended over the range 2 to 80 micrometers.

The process operated on a 24 hour per day basis at an approximately constant input feed rate and quality. The 4 precipitator banks rapped sequentially on a 30-minute cycle.

SITE 3

Testing was performed at this site in the stack of an oil-fired boiler used for heating purposes only. The rated capacity of the boiler was 100 MBTU/hr. and was fired with #6 oil. Testing was performed in the 1.55 meter diameter stack at a plane 9.15 meters above the boiler breeching and 1.55 meters below the top of the stack. The average stack gas temperature was 250°C, the moisture content was approximately 2% and the carbon dioxide and oxygen compositions were approximately 15% and 4% respectively. The boiler was equipped with forced draft combustion air fans only resulting in stack gas velocities of near 4 meters/sec.

SECTION 5

INSTRUMENT DESCRIPTIONS

BETA GAUGE INSTRUMENTS

General Principle of Operation

In the general case the mass of particulate material filtered from a measured volume of stack gas is determined by the attenuation of a beam of beta particles in passing through the sample.

The attenuation is related to the mass of material by the equation

$$N_i = N_o e^{-Ama} \qquad (1)$$

where N_o is the rate at which beta particles pass through the filter material before collection of the sample,
N_i is the rate at which beta particles pass through the filter material and collected sample,
A is the area of the filter through which the beta particles pass to reach the detector,
m is the mass concentration of sample collected on the filter,
a is the mass absorption coefficient of C^{14} beta particles and is approximately constant for elements with atomic number to mass ratios of 0.45 to 0.50.

Recasting equation (1) we obtain

$$\ln (N_o)/(N_i) = Ama \qquad (2)$$

$$= Km$$

where K is a constant.

Since for a system of constant filter deposition and source-detector geometry, m, the mass concentration is linearly related to total mass of deposition, M, by the ratio of the deposit area to the area through which the beta particle pass.

Thus

$$M = K' \ln (N_o)/(N_i) \quad (3)$$

where K' is a constant.

If the volume of the gas passed through the filter under stated conditions is V, the mass concentration of the gas under the same conditions is given by

$$M/V = K'/V \times \ln (N_o)/(N_i) \quad (4)$$

From equation (4), measurement of particulate concentration in a gas stream is derived from measurement of the sampled gas volume and the rate at which beta particles are received after passing through the clean filter and the same filter with particulate deposit. This relationship is the basis upon which the beta gauges operate.

More detailed descriptions of the actual instruments manufactured by Lear Siegler Inc. and Research Appliance Corporation used in this program are presented in Appendices A and B, respectively.

MANUAL METHOD

The manual method of emissions testing was performed using a Scientific Glass Blowing sampling train conforming to the requirements detailed in Method 5 of the Federal Register 36, #247 Part II (Dec. 23, 1971) (Ref. 1). In this technique particulate material is withdrawn isokinetically from the stack through a heated probe.

The particulate material is removed primarily by a cyclone and back-up filter system. The particulate catch includes however all particulate material retained on the walls of the probe and glass-ware up to and including the filter holder. This fraction of the particulate catch is collected by brushing and washing the contaminated surfaces, and evaporating these washing to dryness.

Further details of the design and operation of this manual test method are presented in Appendix C.

SECTION 6

TEST PROGRAM

The purpose of the test program was to compare the particulate emission rate of each beta gauge with the rate determined by the manual method recommended by EPA and known as Method 5 as detailed in Ref. 1. This method is the reference method.

During each test run the beta gauges were operated automatically at the measurement rate determined optimum for each site. Test runs were performed using the manual method as detailed before. Comparison was made of the average beta gauge emission rate measurement during the manual test run and the manual method emissions rate measurement.

TEST PROGRAM, SITE 1

Originally the program was planned to compare the particulate emission rate as measured by the two beta gauges and the manual method, under the following conditions:

1. Single point beta gauge measurement with full traversing of the manual method.
2. Single point beta gauge measurement with single point measurement by the manual method.

However due to mechanical and electrical problems with the Research Appliance Company instrument, tests were conducted to compare only the Lear Siegler instrument with the manual method. Table 1 details the program and identifies the test points shown in Figure 1. Table 2 summarizes the test conditions.

Table 1. TEST PROGRAM - SITE 1

Day	Date	Lear Siegler Port	Lear Siegler Position	Clean Probes	EPA Trains No. 1 Hour Runs Traversing	EPA Trains No. 1 Hour Runs Single Point
1	1/17	1	Centroid 3		2	
2	1/18	1	Centroid 3		2	
3	1/19	1	Centroid 4		-	
4	1/20	1	Centroid 4		-	
5	1/21	1	Av.Velocity		2	
6	1/22	1	Av.Velocity	x	2	
7	1/23	1	Av.Velocity			2
8	1/24	1	Av.Velocity			2
9	1/25	1	Av.Velocity			2
10	1/26	1	Av.Velocity			-
11	1/27	1	Av.Velocity			-
12	1/28	1	1		2	
13	1/29	1	2	x	2	
14	1/30	1	5	x		2
15	1/31	1	6			2
16	2/ 1	2	Centroid 3			2
17	2/11	2	Centroid 3			2
18	2/12	2	Centroid 4		2	
19	2/25	2	Av.Velocity		2	
20	2/26	2	Av.Velocity			2
21	3/11	2	1		2	
22	3/12	2	2	x	2	
23	3/13	2	5			2
24	3/14	2	6			2
25	3/15	2	Av.Velocity			2
26	3/16	2	Av.Velocity			
	3/18			x		

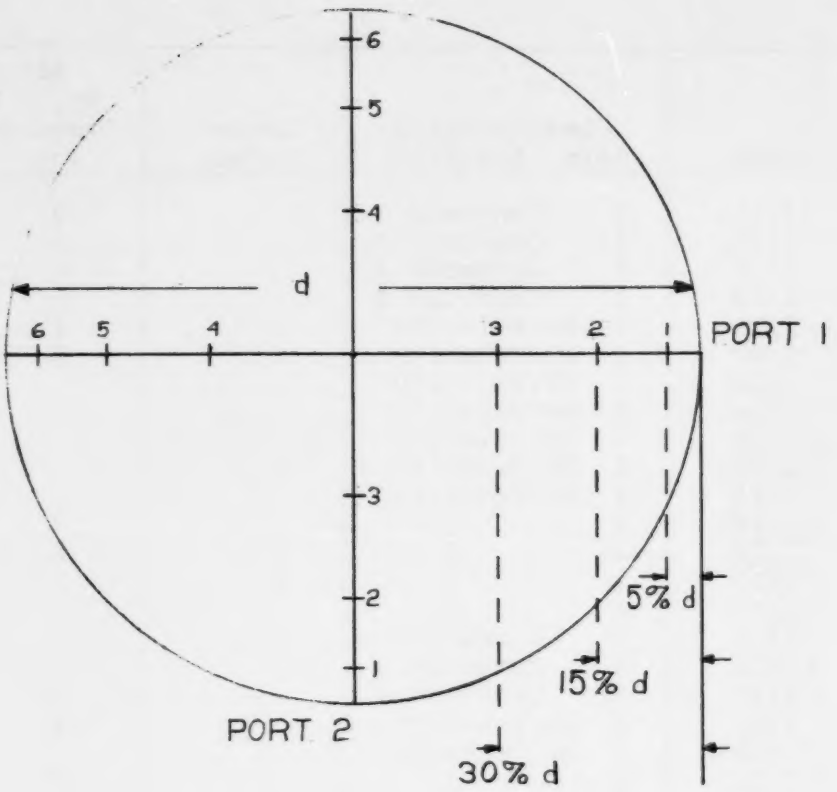


Figure 1. Point Location

Table 2. PROGRAM TEST CONDITIONS - SITE 1

No. Days run	26
No. LSI test days	26
No. RAC test days	0
No. Manual tests total	42
Traversing	20
Single point	22
No. Probe cleaning	4
Days run between cleaning	1,4,6,9
Actual days between cleaning	1,4,6,41

TEST PROGRAM, SITE 2

Examination of the data obtained from site 1 showed little or no valid statistical relationship between the emission rates measured by the beta gauge instrument and the manual method. It was therefore decided that the tests performed at site 2 would be conducted to provide more data under similar test conditions, rather than to attempt investigation of many variables. Thus at site 2 the nozzles of all three instruments were located within the central velocity plateau of the gas flow. They were located closely enough together to provide reasonably similar gas conditions without creating nozzle induced disturbances.

26 one-hour test runs were made with the manual method with the precipitator operating under normal conditions. 6 half-hour runs were performed during which time certain fields of the precipitator were switched off in order to create a higher emission dust loading.

TEST PROGRAM, SITE 3

30 one-hour runs were performed with the manual method when all three nozzles were located in the central velocity plateau region of the stack.

SECTION 7

FIELD EXPERIENCE

SITE 1

Stack Characteristics

The data developed during the tests showed the stack gas quality to be extremely variable in temperature, and particulate loading during normal calciner operation. Gas velocity and moisture content were largely constant during normal operation. During calciner idle operation when temperature only was maintained without any material throughput, effluent particulate loadings were low and exhibited small absolute variations in emission rate.

During normal operation the following ranges were experienced:

gas velocity mps	3.3-4.2
gas temperature ^{o}C	260-370
moisture %	15- 18
particulate loading mg/m^3	250-850

During idle operation the following ranges were experienced:

gas velocity mps	3.3-4.2
gas temperature ^{o}C	260-370
moisture %	5- 6
particulate loading mg/m^3	15- 45

In the early stages of testing the calciner operated essentially 24 hours per day, 5 days per week. Later in the tests, plant processing difficulties reduced operational time to essentially 16 hours per day, 5 days per week.

Argos I: Lear Siegler Inc.

The following problems were encountered in operation of the Argos I and attempts were made by Lear Siegler to find solutions.

1. Condensation of water from the sampled gas in the pump and immediate pump connections caused repeated damage to the rotary vane type of pump.

A condensate knock-out jar was added upstream of the pump, and the air by-pass system, used to control sampling rate, was heated to raise the dew point. These modifications did not entirely correct the problem and a Roots blower was subsequently used. Since this type of pump does not rely upon the free movement of carbon or other vanes, and since a high torque electric motor was used to drive the pump, it was hoped that the system would have a greater tolerance to condensation. Despite this, some fouling of the pump occurred which during shut-down conditions caused severe sticking of the pump motor. Additional condensate control is needed under cold ambient temperature and high stack-gas moisture conditions.

2. Deposition in the probe was a recurring problem despite efforts to heat the probe to avoid condensation. No cure was found for this cause of loss of sample prior to collection on the filter tape.

3. The probe solenoid valve was subject to particulate contamination and consequent jamming. As in the case of probe deposition no permanent solution to the problem was found. Frequent cleaning by-passed the problem.

4. Deposition occurred inside the tubes within the instrument. Most deposit formed in the bell-housing and vertical tube above the filter tape. However material collected in the orifice meter downstream of the filter. This had the effect of modifying the orifice calibration and thus changing the volume of gas sampled. More importantly it indicated a leakage of particulate through or around the filter. Since the material was red in appearance the possibility was discounted that the build-up was of volatile material cooling and condensing on expansion after the orifice. No solution was found to this problem.

5. During operation of the instrument an electronic failure occurred in the counting circuit. The failure was diagnosed by Lear Siegler personnel and corrected.

With the exception of the above listed particulate fouling problem, the instrument operated well during the test period, seemed to be unaffected by extremes of cold and other winter environmental factors, and was easy to install and relocate at the site.

Stack Monitor Model 2412: Research Appliance Co.

This beta gauge failed to operate satisfactorily during the entire test period. Problems were encountered in the computer control system, the gas flow measurement and moisture control unit. Prior to termination of the test period the instrument was returned to the manufacturers for modification and check-out.

Valid data was not obtained with this instrument and thus neither field data nor its analysis is presented for the RAC instrument at this site.

Manual Method

The manual method was performed as detailed in Reference 1 with the exception that single point measurements were made as indicated in Table 1. Duplicate one-hour tests were performed each day. Operation parameters such as nozzle size and nomograph settings are shown on the copies of typical raw data sheets presented in Appendix D.

SITE 2

Stack Characteristics

The cement calcining kiln operated at near constant conditions throughout the test period. Typical parameter values were:

gas velocity mps	13.7
gas temperature ^{o}C	182
moisture %	29- 34
particulate loading mg/m^3	20- 1009

The high emission rates observed were due to the deliberate reduction of precipitator efficiencies by sequentially switching off selected fields. Under normal conditions the particulate loading ranged from 20 to 200 mg/m^3.

Argus I: Lear Siegler Inc.

There were no significant mechanical problems with this instrument. However, the high moisture content of the stack gas showed problems in filter tape moisture pick up. This was evidenced by tape breakage and visible wet spots.

Additional tape heaters were installed and appeared to correct the condensation problem.

Stack Monitor Model 2412: Research Appliance Co.

There were no significant mechanical problems with this instrument. However, the computer control program occasionally failed and automatically shut off further automatic instrument operation. It was not determined whether brief line interrupts were the cause of this.

Manual Method

No unusual problems were encountered in using the manual instrumentation.

SITE 3

Stack Characteristics

The oil fired boiler was used for heating purposes only. Since more than one boiler was needed to supply sufficient stream for the total load, it was possible to operate this boiler under near constant conditions.

Typical parameters were:

gas velocity mps	3.8-5.0
gas temperature ^{o}C	227-271
moisture %	2
particulate loading mg/m^3	61-150

Argos I: Lear Siegler Inc.

Mechanical and electrical problems were encountered which required constant attention during testing of this site. These problems centered around failure of the tape transport and bypass valve solenoid control systems and electric failure of the counting circuitry. The instrument failed to operate for 168 hours.

Stack Monitor Model 2414: Research Appliance Co.

Dilution air-line freeze-ups caused some problems which were overcome by use of heating tapes and moisture knock-out jars. Problems were also encountered by chattering of the dryer drain solenoid valve. The cause of this malfunction was not established.

Manual Method

No unusual problems were encountered in using the manual method.

SECTION 8

CALIBRATION CHECKS OF BETA GAUGES

At sites 1, 2 and 3, tests were performed to deposit stack particulates on preweighed pieces of filter. The mass collected was monitored by the beta instruments and the filter pieces were returned to the laboratory for gravimetric analysis.

At sites 2 and 3 attempts were made to introduce known masses of particulate material into the probe nozzles of the beta instruments. Comparison was attempted of the known mass introduced and the mass as measured by the beta gauges. Both coarse and fine powders were used and were introduced as aerosols from a squeeze bottle and as bulk powders by pouring.

At site 3 a check was made of the quantity of material passing through one thickness of filter paper by inserting up to 3 layers in the sampling stage of the Lear Siegler instrument.

Instrument drift of the Lear Siegler was observed using the built-in zero and reference calibrate conditions. The RAC instrument does not have these automatic calibrate-check capabilities.

SECTION 9

RESULTS

Typical field data sheets and data tabulations are presented for sites 1, 2 and 3 in Appendices D, E and F. Details of the statistical analysis are presented in Appendix G.

Since considerable deposition of particulate material was observed in the probe system of the Argos I, analysis has been performed using both the total particulate and filter catch only of the manual method as reference. The occurrence of particle deposition in the RAC instrument is masked by the back-purge system, and no direct estimate of the extent of deposition could be determined.

Tables 3, 4 and 5 summarize the data obtained for sites 1, 2 and 3 respectively and show the filter-only and filter-plus-probe-washings base for comparison.

Regression analysis was performed and is summarized in Table 6.

The spread of the data and the regression lines are shown in Figures 2 through 11.

The quantities of the particulate material removed from the probe and pre-filter pipe-work on the beta gauge are shown in Table 7.

Alumina powder in the 10 micrometers size range and sodium bicarbonate in the size range up to 150 micrometers were used for these tests. Deposition of both these powders in the probe system generally resulted in near zero mass readings by the beta gauges. Examination of and cleaning of the probe systems after these test confirmed that the majority of the powders introduced into the probe tip failed to reach the filter tapes.

Up to 3 layers of filter tape were placed simultaneously in series in the filter holder of both beta gauge instruments at site 3. Visual examination of the three layers of filter tapes showed discoloration of all three, indicating passage of material through the filter medium. Gravimetric analysis showed that approximately 2% of the sample was passing the first filter and a gravimetrically undetectable quantity passed the second filter.

Table 3A. SITE 1 - DATA FOR L.S.I.

OBSERVATIONS WITH FILTER CATCH ONLY AS REFERENCE

Reference Observation Mg/M^3	LSI Observation Mg/M^3	LSI% Change from Reference
170.9	473.5	177.1
120.4	358.3	197.6
127.2	359.5	182.6
39.5	102.8	160.1
12.5	49.4	296.0
112.8	406.5	260.4
222.4	393.6	77.0
50.2	381.6	660.2
201.3	339.0	68.4
200.6	392.2	95.5
183.1	379.9	64.5
210.7	357.7	69.8
10.8	72.9	57.5
254.3	183.7	- 27.8
43.0	95.5	122.0
245.3	92.9	- 62.1
145.9	59.2	- 59.5
62.9	304.7	384.3
222.2	349.2	57.2
212.0	263.9	24.5
202.8	302.1	49.0
131.2	267.4	103.9
63.4	312.2	392.4
217.9	303.9	39.5
216.2	432.7	105.9
247.0	240.9	- 2.5
247.9	236.2	- 4.7
253.1	279.9	10.6
227.5	263.3	15.7
97.0	345.5	256
257.3	422.2	107.5
93.4	328.0	251

Average = 145.2 Std. Dev. = 170.4

Note: if the reference value was under 10 Mg/M^3, it was omitted from this calculation due to the sensitivity of this type of measurement to such readings.

Table 3B. SITE 1 - DATA FOR L.S.I.

OBSERVATIONS USING FILTER CATCH PLUS PROBE WASHINGS AS REFERENCE

Reference Observation Mg/M^3	LSI Observation Mg/M^3	LSI% Change from Reference
265.6	473.5	78.3
260.1	358.3	37.8
235.5	359.5	52.7
48.0	102.8	114.0
16.6	49.4	198.4
213.4	406.5	90.5
286.5	393.6	37.4
56.5	381.6	575.9
473.3	339.0	- 28.4
219.6	392.2	78.6
334.2	422.2	26.6
237	379.9	60.3
287.0	357.7	24.6
75.3	82.5	9.5
28.5	72.9	155.8
292.3	183.7	- 37.2
147.7	95.5	- 35.3
297.5	92.9	- 68.8
281.7	59.2	- 79.0
214.5	304.7	42.1
347.1	349.2	.6
255.9	263.9	3.1
232.9	302.1	29.7
192.0	267.4	39.3
139.6	312.2	123.6
489.9	303.9	- 37.9
546.8	432.7	- 20.9
457.8	240.9	- 47.4
440.6	236.2	- 46.4
567.8	278.9	- 50.7
408.2	263.3	- 35.5
252.6	345.5	368
343.2	328.0	- 4.4

Average = 40.1 Std. Dev. = 116.2

Table 4A. SITE 2 DATA FOR RAC AND LSI -
OBSERVATIONS WITH FILTER CATCH ONLY AS REFERENCE

Reference Observation Mg/M^3	RAC Observation Mg/M^3	LSI Observation Mg/M^3	RAC % Change from Reference	LSI % Change from Reference
11.04	12.82	15.31	+ 16.2	+ 38.7
10.25	4.36	12.74	- 57.5	+ 24.3
18.38	18.74	30.90	+ 2.0	+ 68.1
25.17	18.61	28.50	- 26.1	+ 13.2
21.19	18.74	27.52	- 11.6	+ 29.9
28.39	24.58	30.83	- 13.3	+ 8.6
27.26	19.87	27.21	- 26.2	- .2
13.82	1.65	16.36	- 88.4	+ 18.4
12.15	.18	14.49	- 98.5	+ 19.3
38.52	32.16	45.93	- 16.5	+ 19.2
44.86	27.10	46.89	- 39.6	+ 4.5
69.64	42.34	79.28	- 39.2	+ 13.8
93.98	58.48	139.30	- 37.8	+ 48.2
188.40	139.60	184.40	- 25.9	- 2.1
228.80	142.30	220.40	- 37.8	- 3.7
185.20	129.20	183.50	- 30.2	- 0.9
221.30	99.97	176.90	- 54.8	- 20.1
18.48	2.49	31.32	- 86.5	+ 69.4
12.19	1.53	18.68	- 87.4	+ 53.2
		Average=	- 40.0	21.2
		Std. Dev=	31.9	24.8

Note: If the reference value was under 10 Mg/M^3, it was omitted from this calculation due to the sensitivity of this type of measurement to such readings.

Table 4B. SITE 2 DATA FOR RAC AND LSI - OBSERVATIONS WITH FILTER CATCH PLUS PROBE WASHINGS AS REFERENCE

Reference Observation Mg/M^3	RAC Observation Mg/M^3	LSI Observation Mg/M^3	RAC % Change from Reference	LSI % Change from Reference
119.20	23.89	28.45	- 80.0	- 76.1
127.80	12.82	15.31	- 90.0	- 88.0
87.49	4.36	12.74	- 95.0	- 85.4
98.57	3.72	15.37	- 96.2	- 84.4
86.14	3.22	15.87	- 96.3	- 81.6
98.21	4.59	16.51	- 95.3	- 83.2
62.59	18.61	20.28	- 70.3	- 67.6
216.80	18.87	30.90	- 91.3	- 85.8
90.94	18.61	28.50	- 79.5	- 68.7
142.50	18.74	27.52	- 86.8	- 80.7
158.90	24.58	30.83	- 84.5	- 80.6
137.60	19.87	27.21	- 85.6	- 80.2
26.90	1.65	16.36	- 93.9	- 39.2
20.10	.18	14.49	- 99.1	- 27.9
19.19	.14	9.76	- 99.3	- 49.1
92.22	32.16	45.93	- 65.1	- 50.2
101.30	27.10	46.89	- 73.2	- 53.7
157.30	42.30	79.28	- 73.1	- 49.6
222.30	58.48	139.30	- 73.7	- 37.3
755.90	139.60	184.40	- 81.5	- 75.6
902.60	142.30	220.40	- 84.2	- 75.6
1009.00	129.20	183.50	- 87.2	- 81.8
709.40	99.97	176.90	- 85.9	- 75.1
181.60	2.49	31.32	- 98.6	- 82.8
134.40	1.53	18.68	- 98.9	- 86.1
		Average =	- 86.6	- 69.8
		Std. Dev. =	10.0	17.9

Note: If the reference value was under 10 Mg/M^3, it was omitted from this calculation due to the sensitivity of this type of measurement to such readings.

Table 5A - SITE 3 DATA FOR RAC AND LSI -
OBSERVATIONS WITH FILTER CATCH ONLY AS REFERENCE

Reference Observation Mg/M^3	RAC Observation Mg/M^3	LSI Observation Mg/M^3	RAC % Change from Reference	LSI % Change from Reference
72.25	33.95	61.28	- 53.0	- 15.2
71.79	36.29	60.76	- 49.4	- 15.4
59.14	37.21	43.98	- 37.1	- 25.6
56.14	34.48	44.65	- 38.6	- 20.5
74.84		45.25		- 39.5
68.98		29.10		- 57.8
75.07		44.78		- 40.3
70.21		33.34		- 52.5
64.86		40.43		- 37.6
52.00	28.56	34.89	- 44.0	- 31.6
44.00	25.21		- 42.7	
42.89	24.64	40.32	- 42.6	- 6.0
57.93		35.43		- 38.8
56.69	19.92	38.43	- 64.9	- 32.2
56.87	21.02	31.55	- 63.0	- 44.5
56.72	18.22	30.95	- 67.9	- 45.4
52.73	18.20	28.70	- 65.5	- 45.6
56.98	16.54	20.74	- 70.9	- 63.6
59.36	22.71	25.48	- 61.7	- 57.1
60.13	17.15	22.51	- 71.5	- 62.6
58.55[a]	152.40	19.52	+160.3	- 66.7
79.64	22.12	16.95	- 72.2	- 78.7
62.79	16.16	21.56	- 74.3	- 71.1
65.67	15.91	16.11	- 75.8	- 75.5
51.75	25.91	22.34	- 49.9	- 56.8
60.59	22.24	17.63	- 63.3	- 70.9
54.10	27.08	11.67	- 49.9	- 78.4
50.57	26.34	27.28	- 47.9	- 46.1
49.26	28.25	18.95	- 42.7	- 61.5
51.95	27.19	12.91	- 48.4	- 75.1
		Average =	- 56.4	- 48.0
		Std. Dev. =	12.5	20.3

[a] Rejected as rogue.

Table 5B. SITE 3 DATA FOR RAC AND LSI -
OBSERVATIONS USING FILTER CATCH PLUS PROBE WASHINGS AS REFERENCE

Reference Observation Mg/M^3	RAC Observation Mg/M^3	LSI Observation Mg/M^3	RAC % Change from Reference	LSI % Change from Reference
91.97	33.95	61.28	-63.1	-33.4
88.19	36.29	60.76	-58.9	-31.1
72.96	37.21	43.98	-49.0	-39.7
69.83	34.48	44.65	-50.6	-36.2
99.26		45.25		-54.4
101.20		29.10		-71.2
130.70		44.28		-66.1
146.10		33.34		-77.2
150.90		40.43		-73.2
77.61	28.56	34.89	-63.2	-55.0
103.20	25.21		-75.6	
103.10	24.64	40.32	-76.1	-60.9
69.81		35.43		-49.2
75.52	19.92	38.43	-73.6	-49.1
74.98	21.02	31.55	-72.0	-57.9
96.53	18.22	30.95	-81.1	-67.9
68.83	18.20	28.70	-73.6	-58.3
72.26	16.54	20.74	-77.1	-71.3
88.45	22.71	25.48	-74.3	-71.2
97.38	17.15	22.51	-82.4	-76.9
114.10	15.24	19.52	-33.6	-82.9
139.90	22.12	16.95	-84.2	-87.9
79.90	16.16	21.56	-79.8	-73.0
99.80	15.91	16.11	-84.1	-83.9
80.65	25.91	22.34	-67.9	-72.3
104.50	22.24	17.63	-78.7	-83.1
79.75	27.08	11.67	-66.4	-85.4
75.34	26.34	27.28	-66.0	-63.8
61.03	28.25	18.95	-53.7	-68.9
62.24	27.19	12.91	-56.3	-79.3
		Average =	-65.5	-64.8
		Std. Dev. =	23.6	16.1

Table 6. REGRESSION ANALYSIS OF DATA

	Regression Equation	Standard Error of the Estimate Se	Correlation Coefficient R
SITE 1			
LSI FC + PW	$y' = 279.8 + .323\ (x - 271.1)$	135.1	.381
LSI FCO	$y' = 279.8 + .5588\ (x - 154.7)$	114.8	.378
SITE 2			
RAC FC + PW	$y' = 33.9 + .15\ (x - 230.4)$	13.9	.952
RAC FCO	$y' = 41.8 + .608\ (x - 66.8)$	12.3	.969
LSI FC + PW	$y' = 57.5 + .216\ (x - 230)$	24.8	.929
LSI FCO	$y' = 70 + .9\ (x - 66.8)$	14.3	.980
SITE 3			
RAC FC + PW	$y' = 29.9 + .38\ (x - 86.6)$	26.5	.260
RAC FCO	$y' = 24 + .03\ (x - 57.6)$	6.6	.040
LSI FC + PW	$y' = 30.9 + .05\ (x - 92.1)$	13.2	.098
LSI FCO	$y' = 31.4 + .47\ (x - 60.4)$	12.6	.320

FC = Filter catch
PW = Probe washings
FCO = Filter catch only

Figure 2. FILTER CATCH ONLY AS REFERENCE
LSI INSTRUMENT
SITE 1

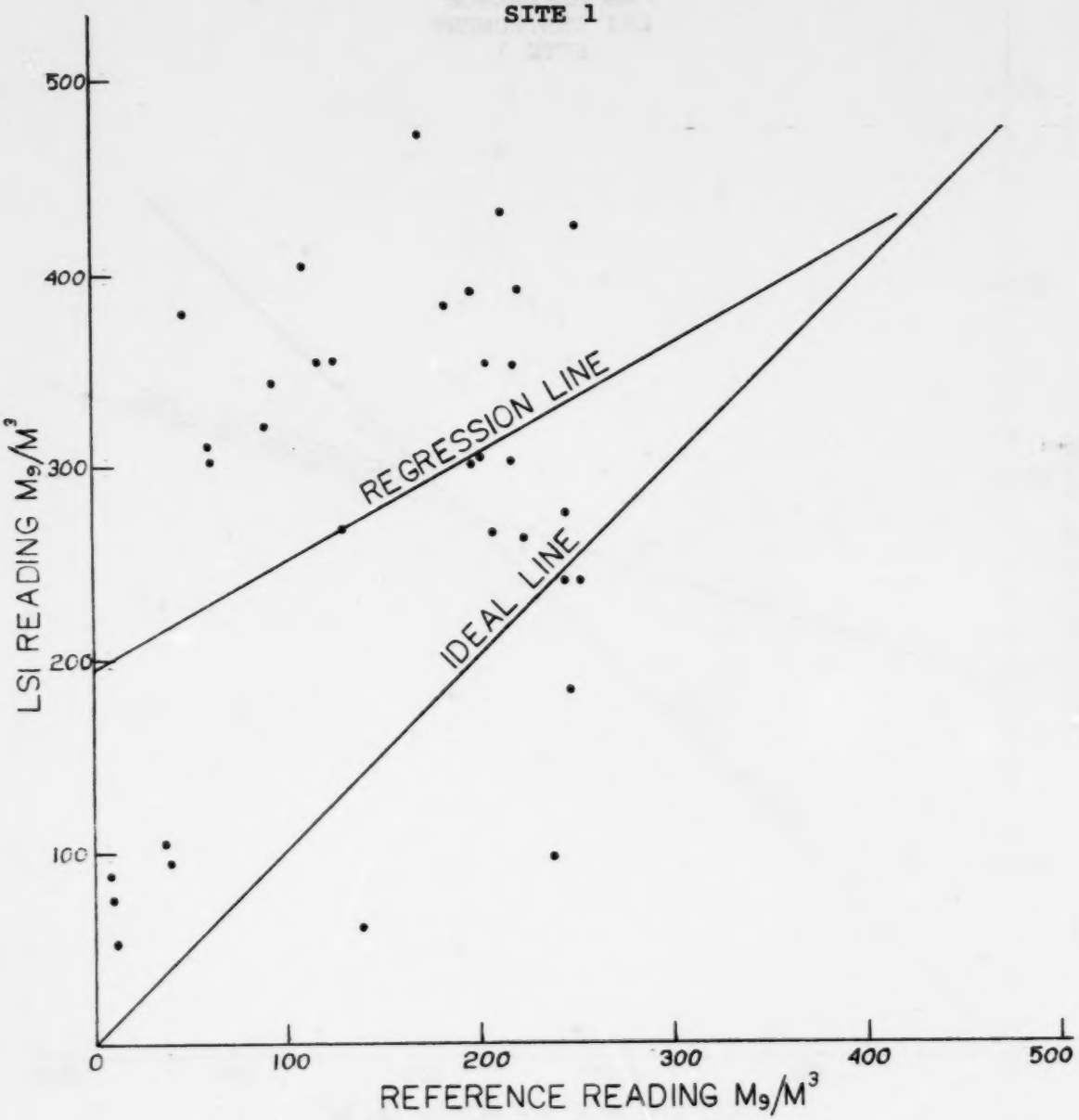


Figure 3. FILTER CATCH PLUS PROBE WASHING
AS REFERENCE
LSI INSTRUMENT
SITE 1

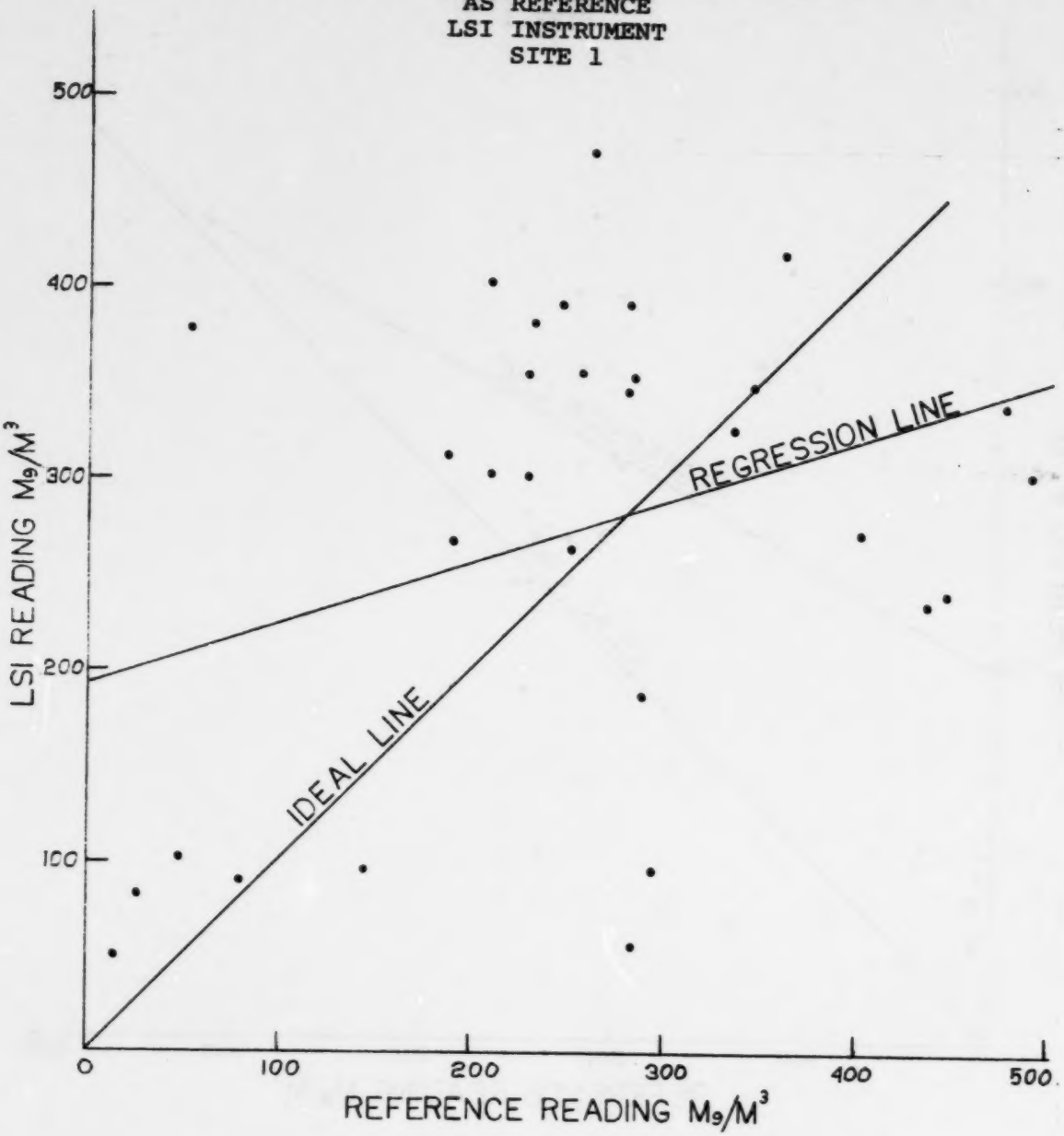


Figure 4. FILTER CATCH ONLY AS REFERENCE
LSI INSTRUMENT
SITE 2

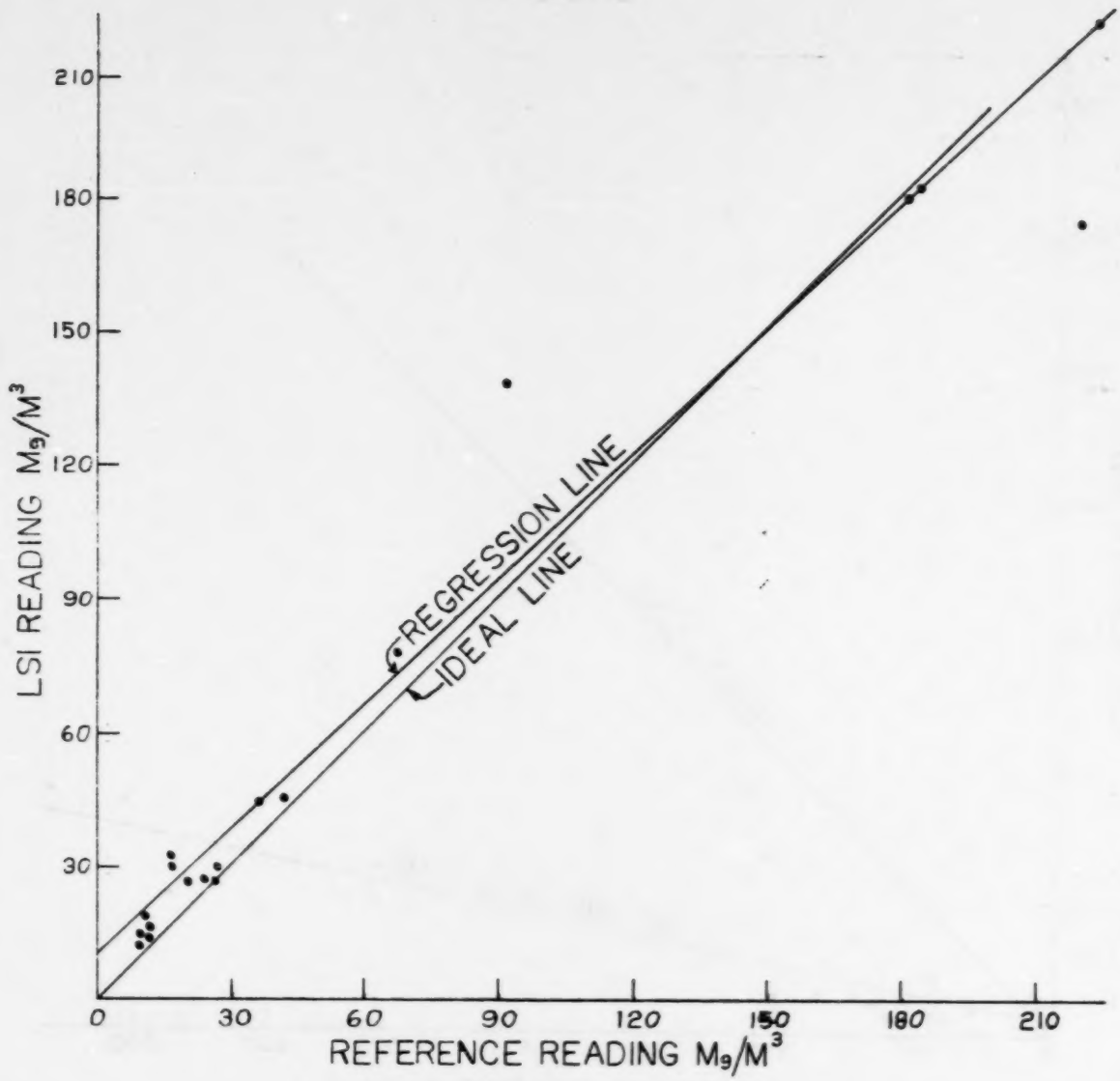


Figure 5. FILTER CATCH PLUS PROBE WASHING
AS REFERENCE
LSI INSTRUMENT
SITE 2

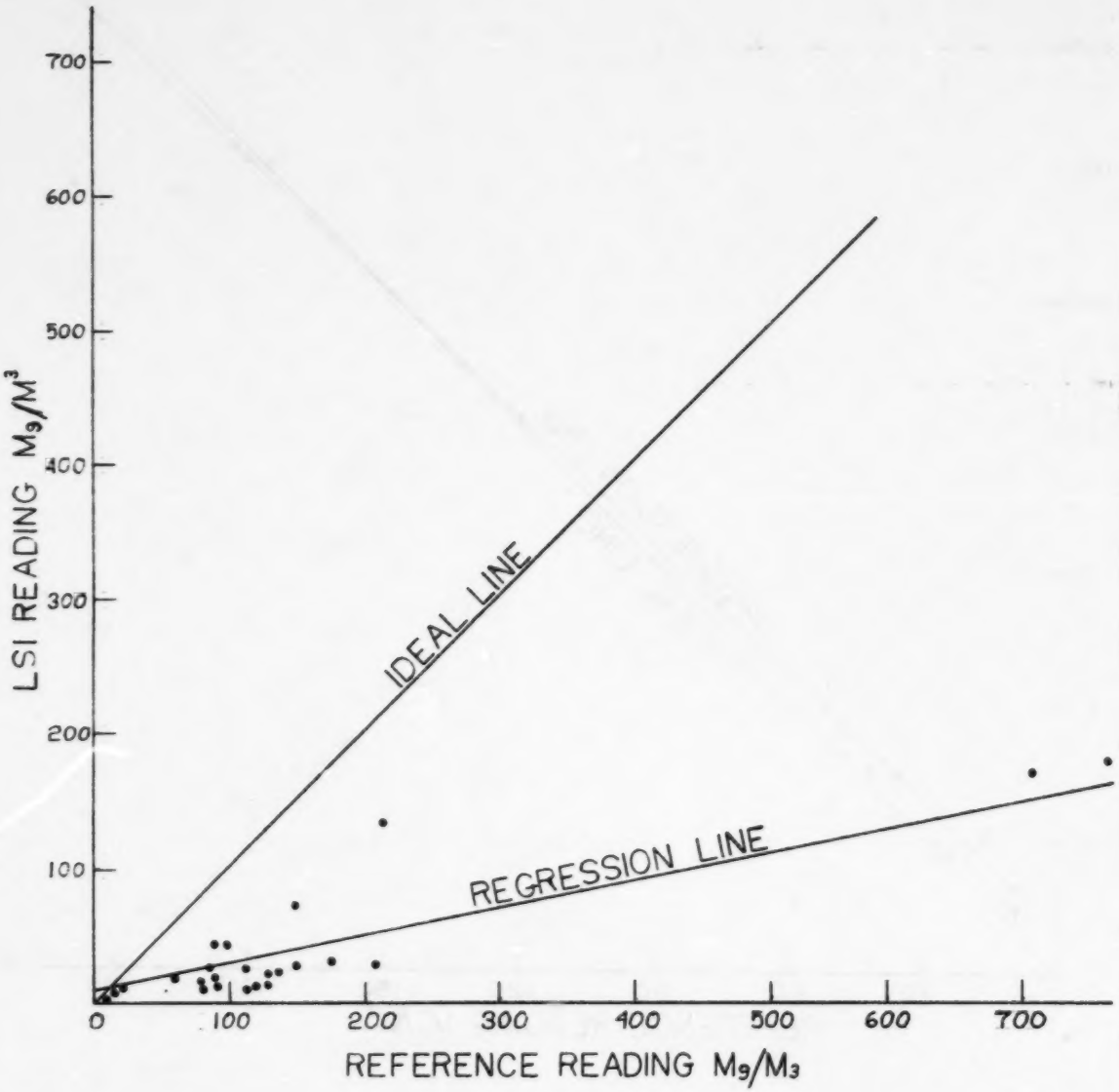


Figure 6. FILTER CATCH AS REFERENCE
RAC INSTRUMENT
SITE 2

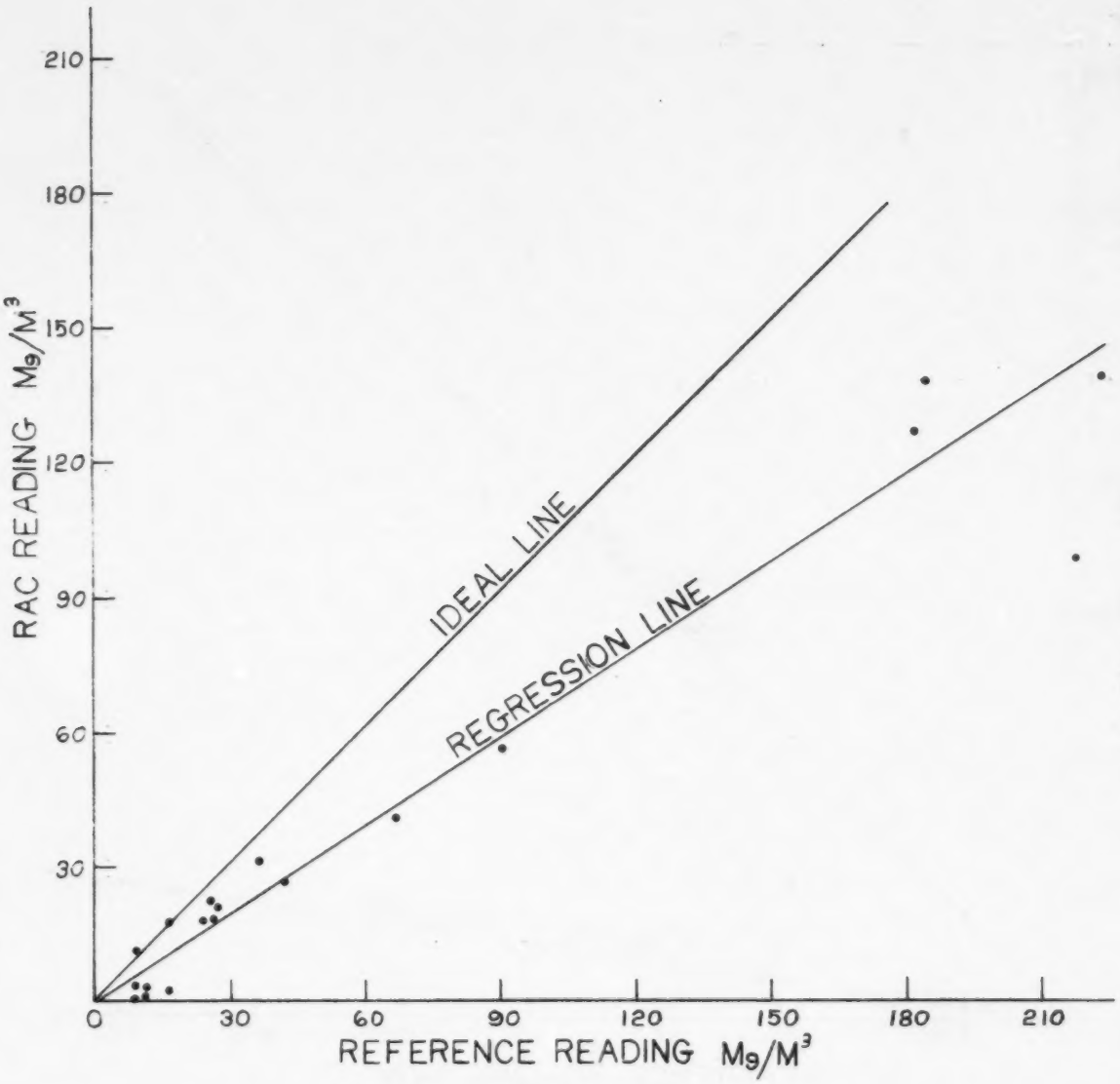


Figure 7. FILTER CATCH PLUS PROBE WASHING
AS REFERENCE
RAC INSTRUMENT
SITE 2

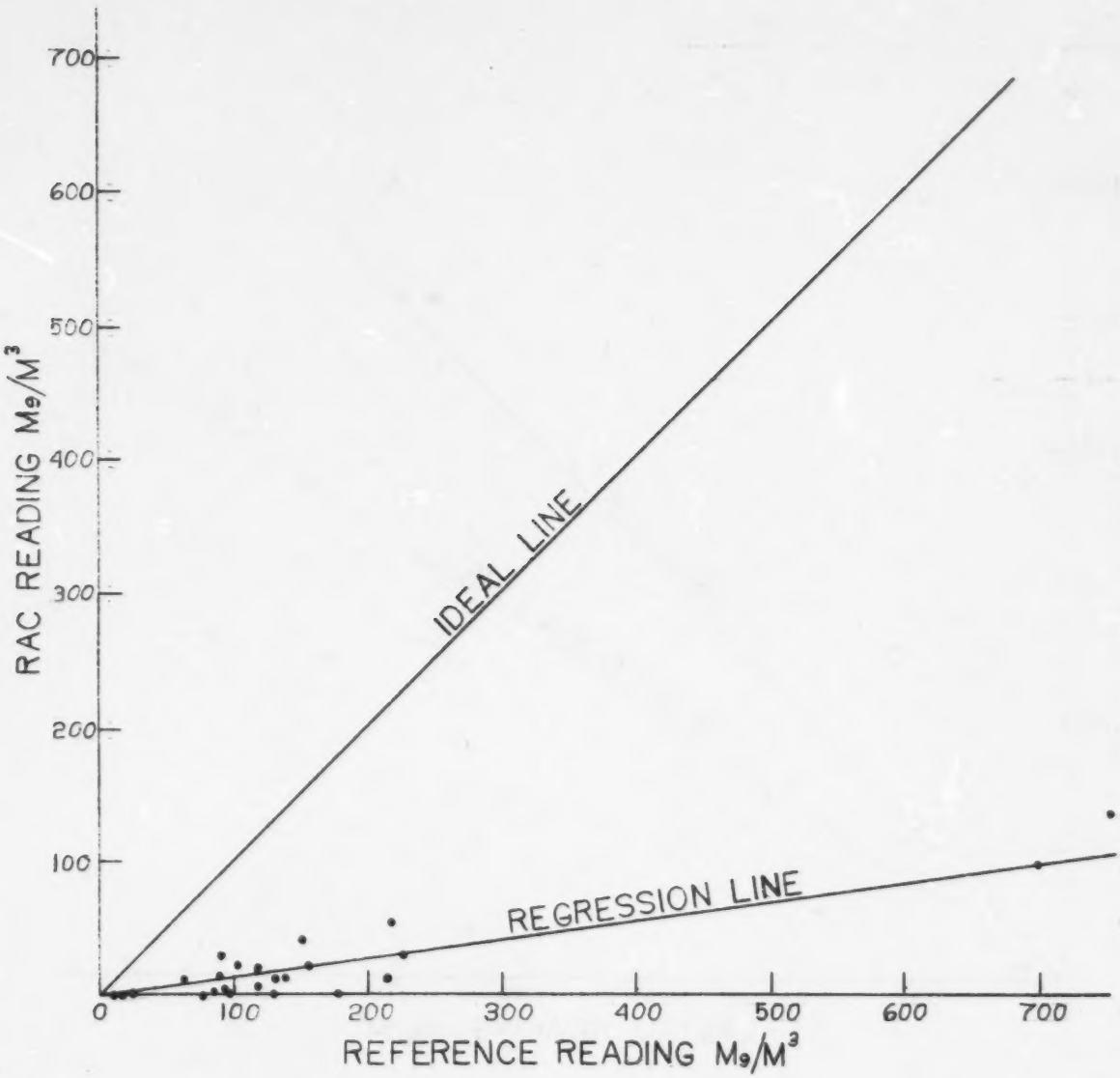


Figure 8. FILTER CATCH ONLY AS REFERENCE
LSI INSTRUMENT
SITE 3

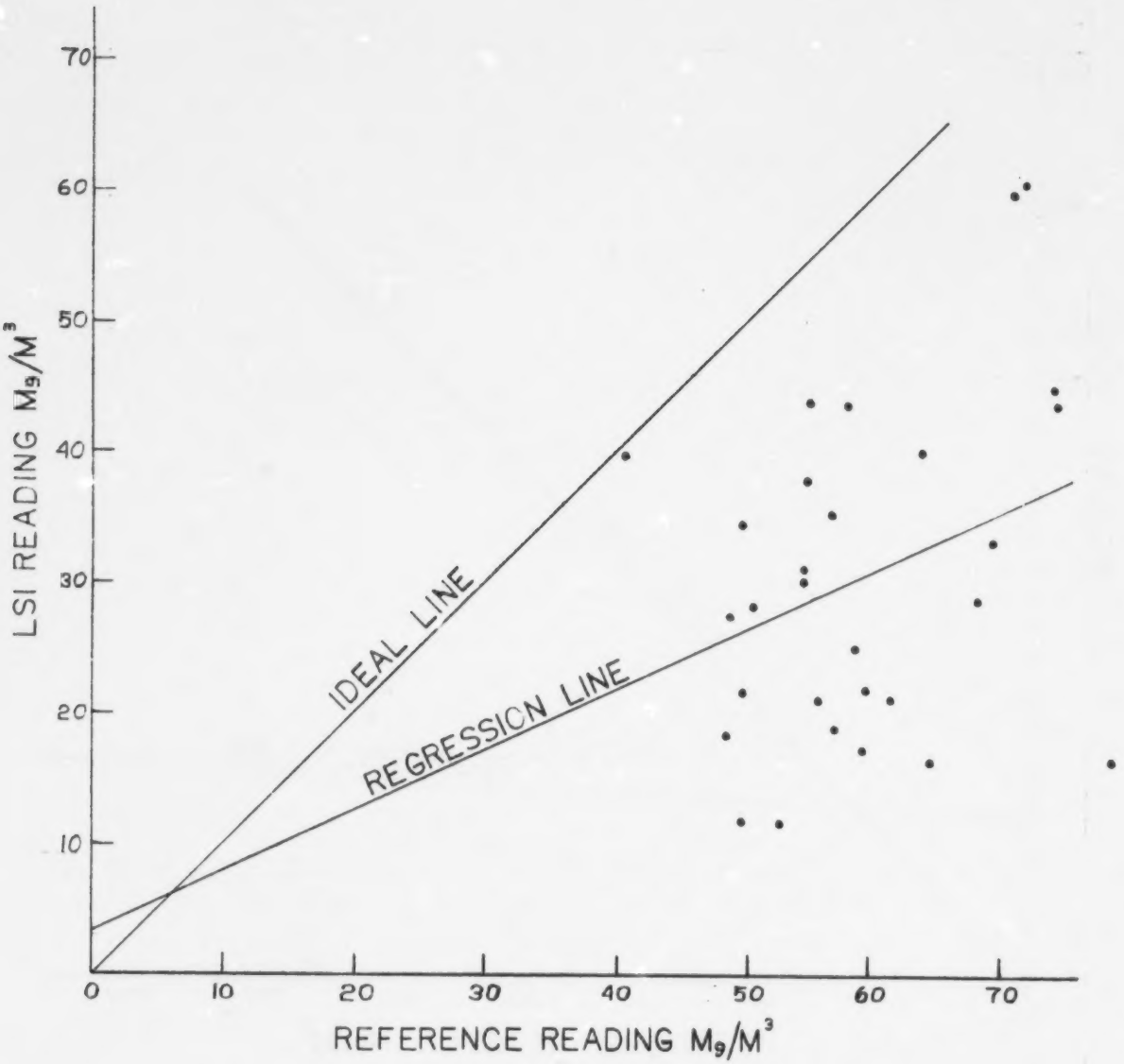


Figure 9. FILTER CATCH PLUS PROBE WASHING
AS REFERENCE
LSI INSTRUMENT
SITE 3

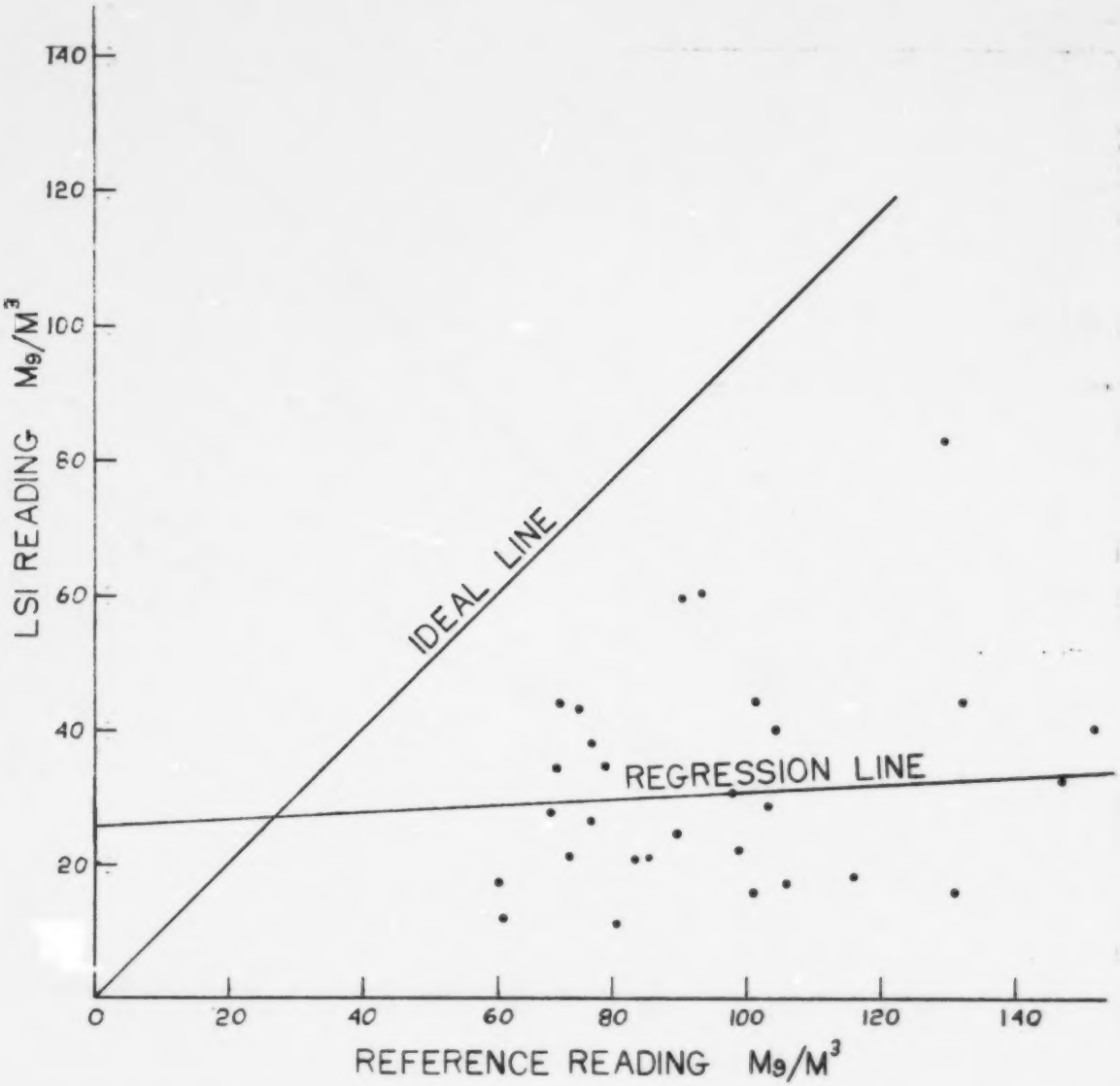


Figure 10. FILTER CATCH ONLY AS REFERENCE
RAC INSTRUMENT
SITE 3

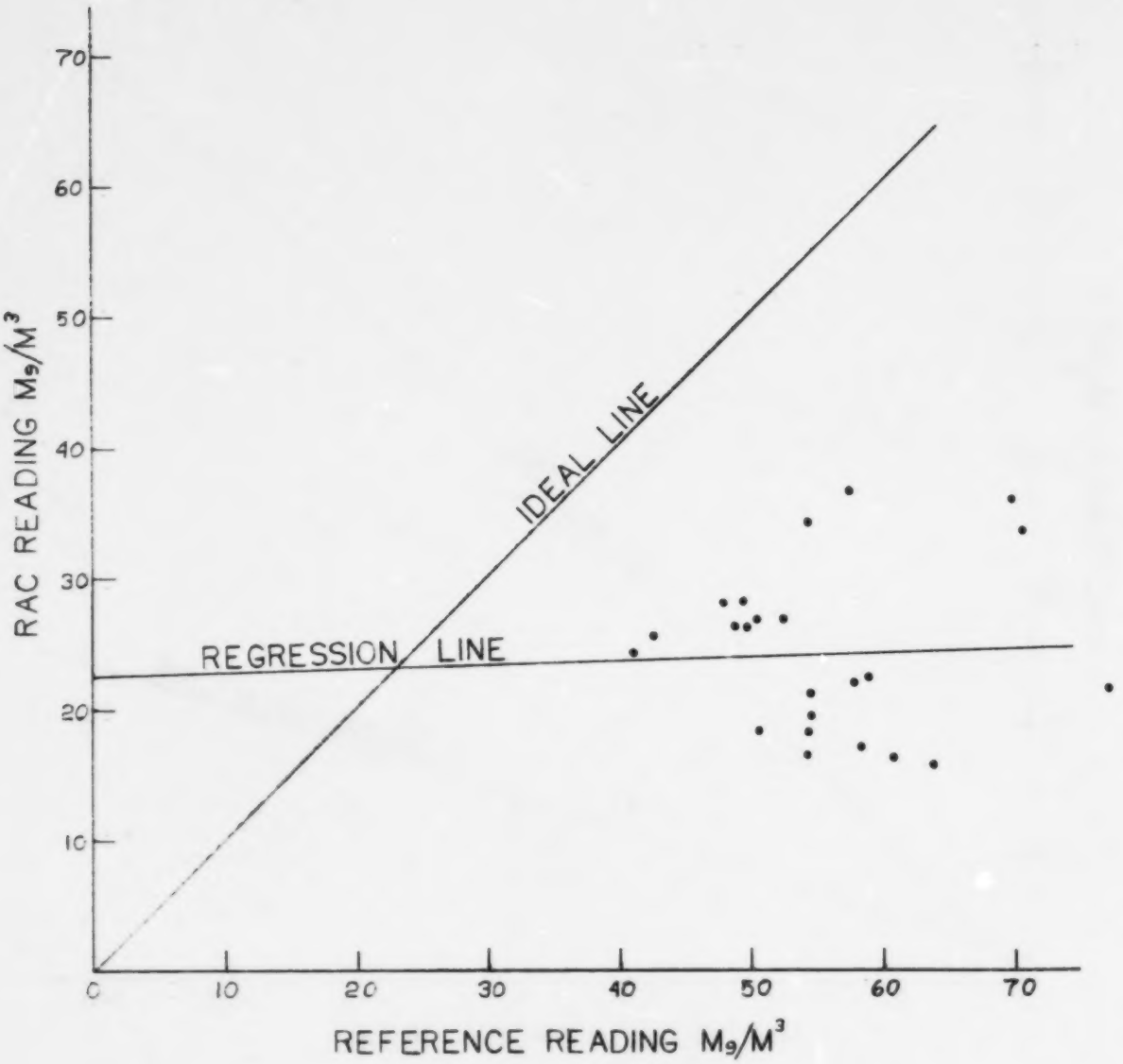


Figure 11. FILTER CATCH PLUS PROBE WASHING
AS REFERENCE
RAC INSTRUMENT
SITE 3

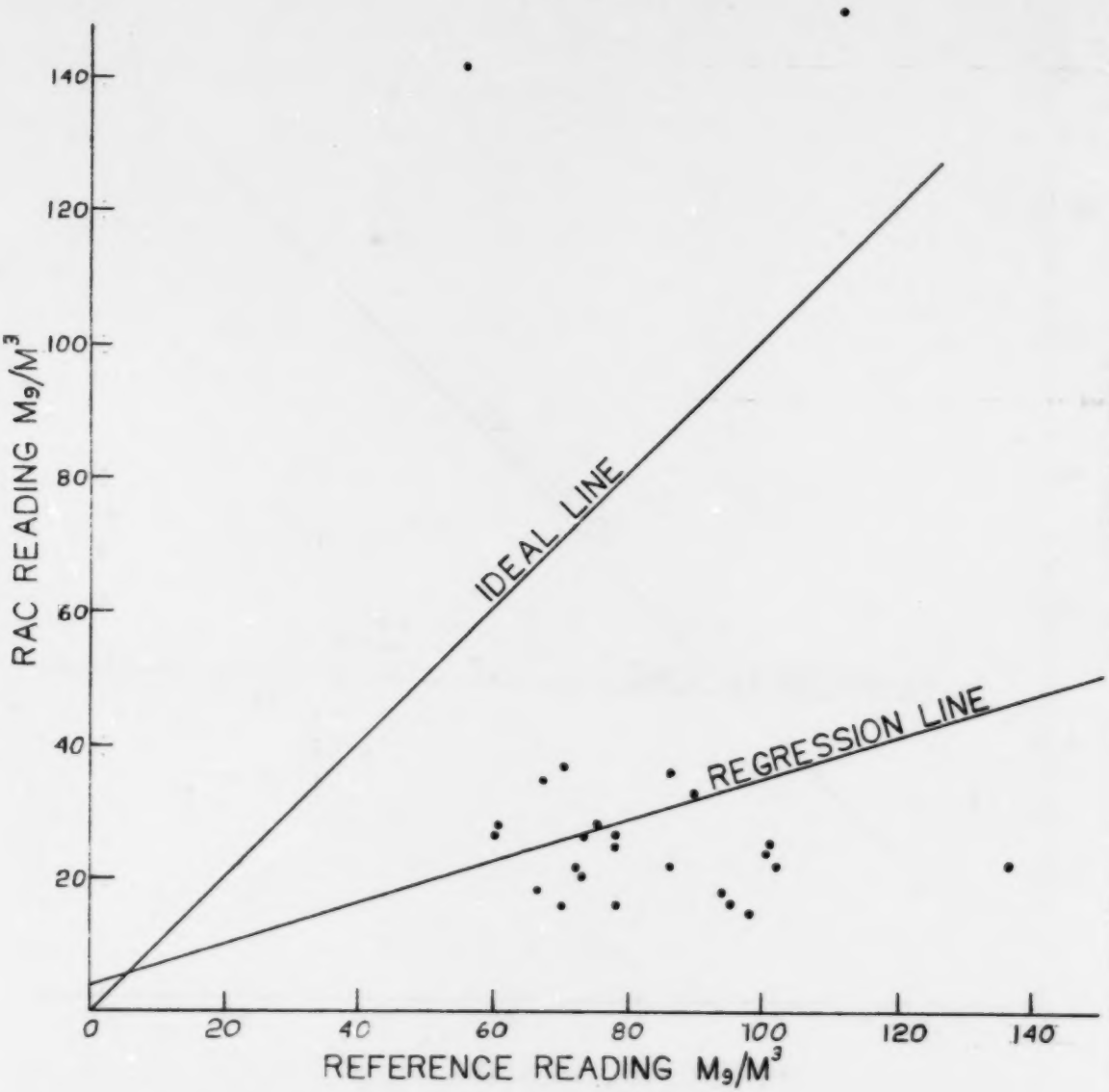


Table 7. MATERIAL MASSES DEPOSITED IN THE PROBE SYSTEM

Site	Date	Days from Previous Washing	Mass material collected grams	
			Lear Siegler	Research Appliance Co.
1	1/22/74	7	10.70	-
	1/28/74	6	5.27	-
	1/29/74	1	5.98	-
	3/12/74	8	28.17	-
	3/18/74	6	25.52	-
2	11/21/74	7	2.67	.54
3	12/11/74	7	0.54	.48

SECTION 10

DISCUSSION

In the analysis of the performance of the particle measuring devices, the performance criteria used were relative accuracy, calibration error, instantaneous drift and long term drift.

Relative accuracy is defined as the difference between the measurement system and the reference system outputs expressed as a percentage of the reference value. Calibration error is defined as the difference between the measurement system reading and the exact concentration of material on a calibration filter, expressed as a percentage of the measurement system reading. Instantaneous drift is defined as the drift in the system between successive readings taken with no time lag between readings. It is expressed in terms of 95% confidence intervals in full scale deflection. Long term drift is defined as the drift in the system between readings of the system taken 24 hours apart. It is expressed in terms of 95% confidence intervals of full scale deflection.

The data of Table 6 clearly shows that the standard error of the estimate for site 1 is sufficiently high to exclude data from this site from further consideration. The data shown in Figures 2 and 3 clearly demonstrate the lack of significant relationship between the particulate emission rates measured by the Lear Siegler and manual reference method.

The flowrate control valve in the sampling system on the beta gauge monitor at site 1 was found to be malfunctioning due to contamination. Higher volumes of air were sampled than was recorded or, in effect, the calibration for flowrate was off. The result was higher mass concentrations with the beta gauge monitor compared to the reference method.

For sites 2 and 3 it will be seen that the standard error of the estimate is not too unrealistic, except perhaps for the values of 24.8 and 26.5. However, the correlation coefficient for site 3 data is unacceptable. The correlation coefficient data for site 2 is good and shows the improvement in correlation for both beta gauges if the filter catch only is used as a basis for comparison.

It is to be concluded therefore that the beta instruments provide valid predictive data for site 2 only and do not provide accurate data at any site. The improvement in correlation coefficient and standard error of the estimate for the filter-catch-only data, indicates that the complex mechanism governing deposition of particulates in the sampling probes is a major factor determining the accuracy of the instruments.

The data shown in Table 7 clearly shows the extent of the line loss problem. The lower value for the RAC instrument is due to the back-purge sequence in the normal operation of the instrument.

Accuracy for sites 2 and 3 using the two reference systems is given in Table 8. Accuracy for site 1 is not suitable for presentation because the data was invalid. Table 8 shows that the best accuracy is given for site 2 when using filter catch only as the basis for comparison. The data clearly show the impact of the line loss of particulates on the accuracy of the measurement.

The calibration errors shown in Table 9 demonstrate the inherent absolute inaccuracy of the beta systems. The RAC unit shows better calibration accuracy than the LSI system, which is to be contrasted with the relative accuracy shown in Table 8.

TABLE 8. ERROR IN RELATIVE ACCURACY
EXPRESSED AS ABSOLUTE MEAN VALUE
PLUS 95% CONFIDENCE INTERVAL

	Site 2		Site 3	
	% Error LSI	RAC	LSI	RAC
FC + PW	105.6	106.6	97.0	112.7
FCO	70.7	104.7	88.6	81.4

TABLE 9. CALIBRATION ERROR
EXPRESSED AS ABSOLUTE MEAN VALUE
PLUS 95% CONFIDENCE INTERVAL

	Site 2		Site 3	
	LSI	RAC	LSI	RAC
Error in %	256.6	211.9	380.5	74.6

Table 10 presents the instantaneous drift of the LSI instrument at sites 2 and 3. The values are in terms of divisions. Similar data cannot be obtained for the RAC instrument since there is no automatic zero check capability.

TABLE 10. INSTANTANEOUS DRIFT
EXPRESSED AS ABSOLUTE MEAN VALUE
PLUS 95% CONFIDENCE INTERVAL,
BOTH FOR DIVISIONS AND IN TERMS OF FULL SCALE READINGS

	Site 2	Site 3
Drift Divs.	5.9	2.72
% of Full Scale	15	7.5

The 24 hour drift data was combined for sites 2 and 3 because of the small amount available. Expressed as absolute mean value plus 95% confidence interval, the 24 hr. drift is 5.8 divisions or in percentage of full scale reading it is 17.4%.

Instantaneous and long term drift data for the LSI instrument shows a maximum error of 17.4% of full scale. The absolute magnitude of this error depends upon the calibrated full scale range of the instruments.

SECTION 11

REFERENCES

1. Federal Register, Vol. 36 #247 Part II, December 23, 1971.

APPENDICES

A. Instrument Design and Operation - Argos 1

B. Instrument Design and Operation - Model 2414

C. Description of the Particulate Reference Method Using the EPA Sampling Train

D. Statistical Analysis

APPENDIX A

INSTRUMENT DESIGN AND OPERATION
ARGOS 1, TRANSPORTABLE MODEL, LEAR SIEGLER INC.

GENERAL DESCRIPTION

The instrument is shown diagramatically in Figure 1 to comprise four main component modules.

Module 1 is the sampling system and comprises a heated stainless steel probe and nozzle. The nozzle was located on a single point while each sample was withdrawn. A motorized ball valve was located in the probe to isolate the instrument from the stack during periods when sampling was not being performed.

A motorized probe designed to sweep across the stack to obtain a representative sample of the entire cross-section of the stack is available for use with the Argos 1, but was not used in the tests reported here.

Module 2 is the Radiometric Measuring Unit and contains the fiberglass filter tape transport, particle filtering stage, beta source and detector systems. The filter tape transport system moves the tape in a precise manner using a metering roll so that sequentially the same area of tape is presented--

(a) to the counting stage where transmitted beta particles are counted over a one minute time period

(b) to the filtering stage where a pre-selected volume of gas is passed through the filter

(c) to the counting stage where transmitted beta particles are counted over a one minute time period

An adjacent clean section of filter tape is then subjected to the same sequence.

The upper fitting of the filter holder is mounted rigidly to the sample transport piping. The lower fitting is moveable by a motor operated cam and connects to the remainder of the sample piping by way of a teflon bellows. The lower portion of the filter housing is pressed up against the filter to provide an air tight seal during a sample cycle and is separated from the filter

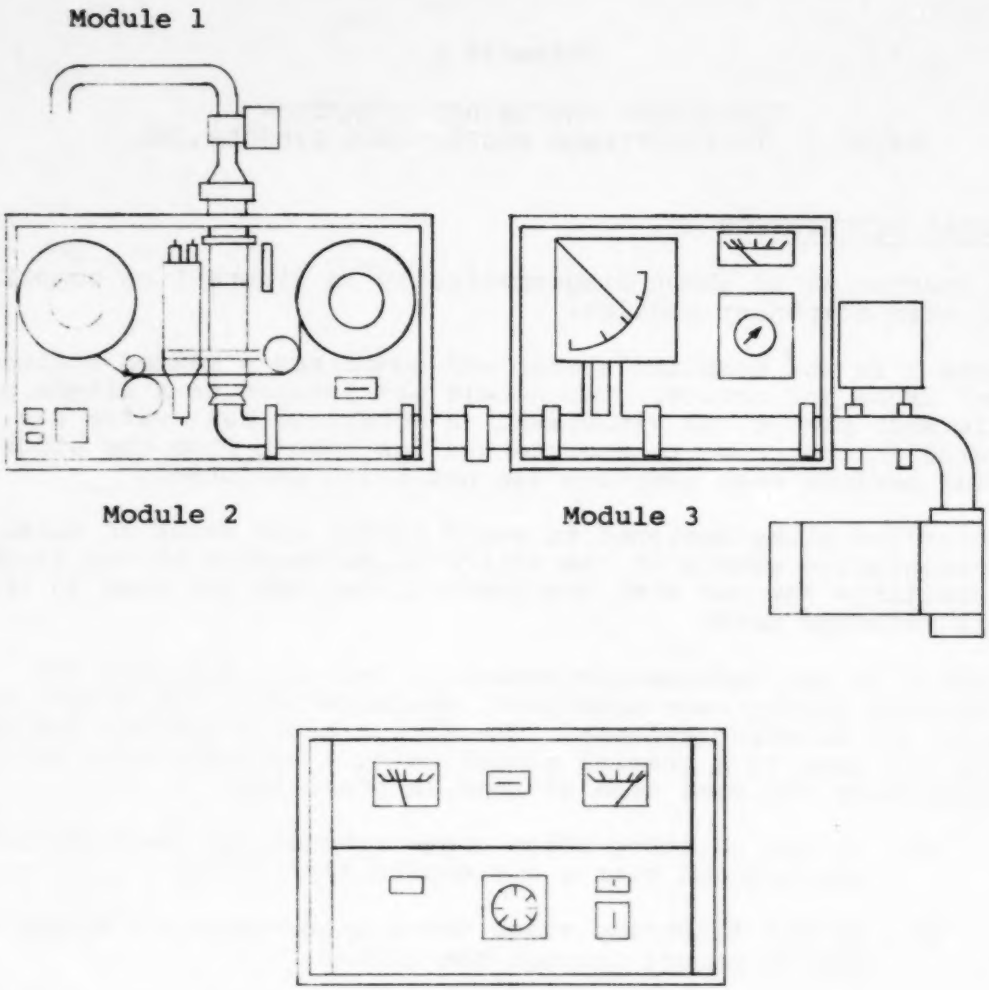


Figure A-1. Argos 1 Mass Analyser

and upper portion of the housing during tape movement. The tape proceeds sample by sample from the storage reel to the takeup reel. The instrument is equipped with an optical tape fault control, that automatically turns the instrument off if the tape tears, or the roll end is reached. This prevents the instrument from taking in unfiltered gas which may cause dust deposition in the transport tubes, orifice and pump. To prevent condensation within the instrument, heating jackets are used over the length of the sample transport pipe. The temperature of the gas is measured with a sensor located just down stream from the filter holder and displayed on a temperature indicator. The temperature is controlled by a thermostat which controls the current to the heating jacket elements.

Module 3 is the Gas Measurement Module and contains a venturi orifice meter and differential pressure regulator that controls the flow through the venturi by activating a motorized vacuum-pump bypass valve. A vacuum gauge and temperature sensor are provided together with the venturi calibration curve, to permit calculation of the sample flow rate. In use, the limit switches on the differential pressure regulator are set above and below a venturi pressure drop value calculated to provide near isokinetic sampling under average conditions. Flow rates of up to 10 M^3/hr are utilized in sampling, and are obtained using either a rotating vane pump or Roots blower. While the sturdy Roots blower is more suitable for permanent operation, it is suggested by Lear Siegler Inc. that the lower weight and easier maintenance rotating vane pump is more suitable for short-time measurements with the transportable system used in this study. Experience however showed the necessity of using the Roots blower under the test conditions.

Module 4 comprises the Computer and Control Unit which controls all the mechanical functions of the instrument, computes the mass concentration as given in Equation 4 and provides an output signal suitable for recording. The entire mechanical sequencing is controlled by a cam timer; the period of sampling is controlled by an adjustable clock timer.

Computation of the ratio of the beta counts is performed by moving voltage potentiometers according to the number of beta impulses received by the G. M. tube. Two scalers are used to suitably match the high rate beta pulses to the low rate potentiometer stepping motors. The ratio of the potentiometer outputs at the conclusion of counting is displayed on a strip chart recorder. The recorder output is manually converted by a chart to mass concentration emission rate.

The control module contains a function switch to permit either a zero check in which the tape is transported and counted without collection of a filtered deposit, or an upscale reference check in which a deposit is simulated by interposing a partially

obscuring plastic plate between the source and detector during the "count sample" event in the sequence.

In this instrument the volume sampled is determined as the product of sampling time and volume flow rate. The sampling time is determined from a timer while the volume flow rate is determined using the orifice meter and differential manometer system. Since volumes measured by venturi meters are dependent upon the temperature and pressure of the gas at the venturi, it is necessary to select the instrument operating parameters to provide a measure of volume flow. Further since both gas temperature and pressure may change during each sampling cycle, it is necessary to establish average parameter values by a reiterative experimental program to establish a reasonable measure of volume flow rate.

Pre-operation Set-up

The instrument was assembled as shown in Figure 1. The section of the probe outside the stack was wrapped with a heating tape and insulated. The sample tubes within the instrument were maintained at a temperature of between 150 and 170 ^{o}C. The measuring range of the instrument is designed to be in the range 0-50 mg collected sample. The sample flow rate and total sampling time must be selected prior to normal operation to give the appropriate concentration range. Figures 2 and 3, relating nozzle size to sampling rate and the venturi flow meter calibration curve are used in the following reiterative manner to establish the required sampling conditions.

1. The maximum anticipated stack gas velocity (V max), static pressure (Ps), temperature (Ts), and dust loading were established by preliminary measurement.

2. Figure 2 was used to select the correct nozzle size based upon V max, to give an actual volume flow rate of between 5 and 9 M^3/hr. The flow rate was determined using Figure 2. Lear Siegler Inc. recommended that this indicated flow rate be increased by 10% to 20% to ensure that the gas sample is always withdrawn from the stack under super isokinetic conditions.

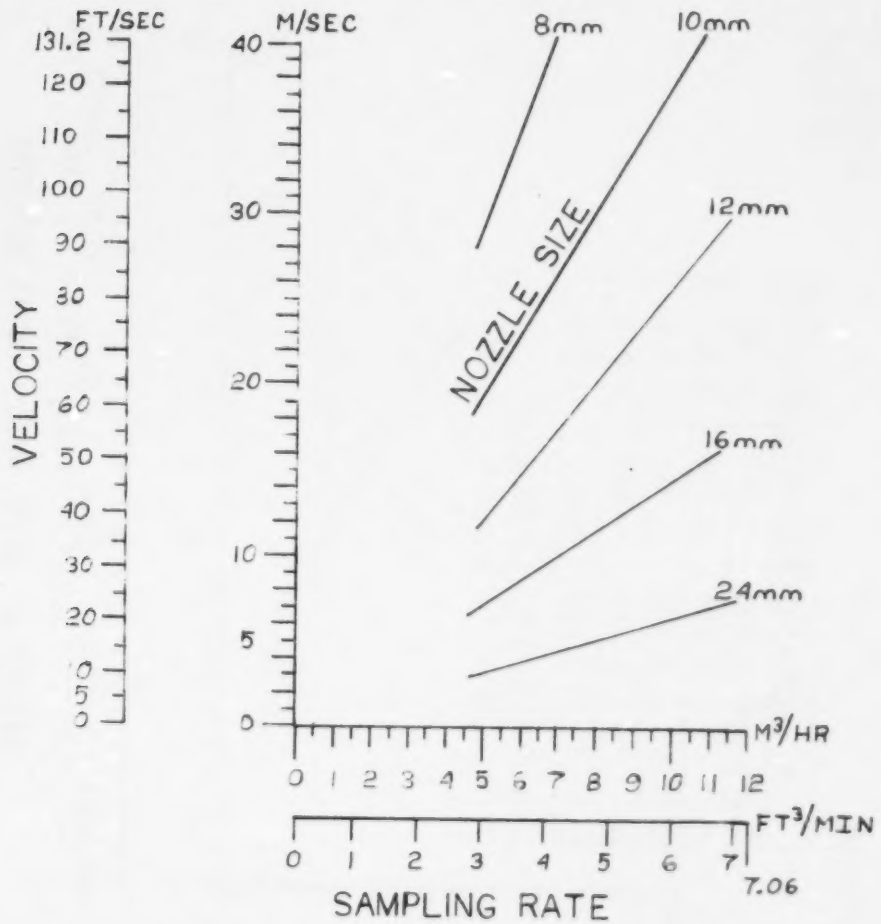
3. The indicated actual sample flow rate was corrected to standard conditions.

4. The desired sample concentration upper limit was established and used to calculate the total sample volume required to equate this concentration to the 50 mg upper design detection limit of the instrument.

5. The desired sampling time was established using the volume flow rate determined in step 2 and the total volume established in step 4 above.

Figure A-2

RELATIONSHIP BETWEEN NOZZLE SIZE & SAMPLING RATE



$Q_V = Q_{ST}(M^3/HR)/C$

$$C = \sqrt{\frac{(1.033 - P_1)\,293}{1.033\,(273 + T)}}$$

P_1	C(t = 50°C)	C(t = 100°C)	C(t = 150°C)
0.1kp cm^2	0.905	0.842	0.791
0.2 "	0.855	0.796	0.747
0.3 "	0.802	0.747	0.701
0.4 "	0.746	0.694	0.652
0.5 "	0.684	0.637	0.598

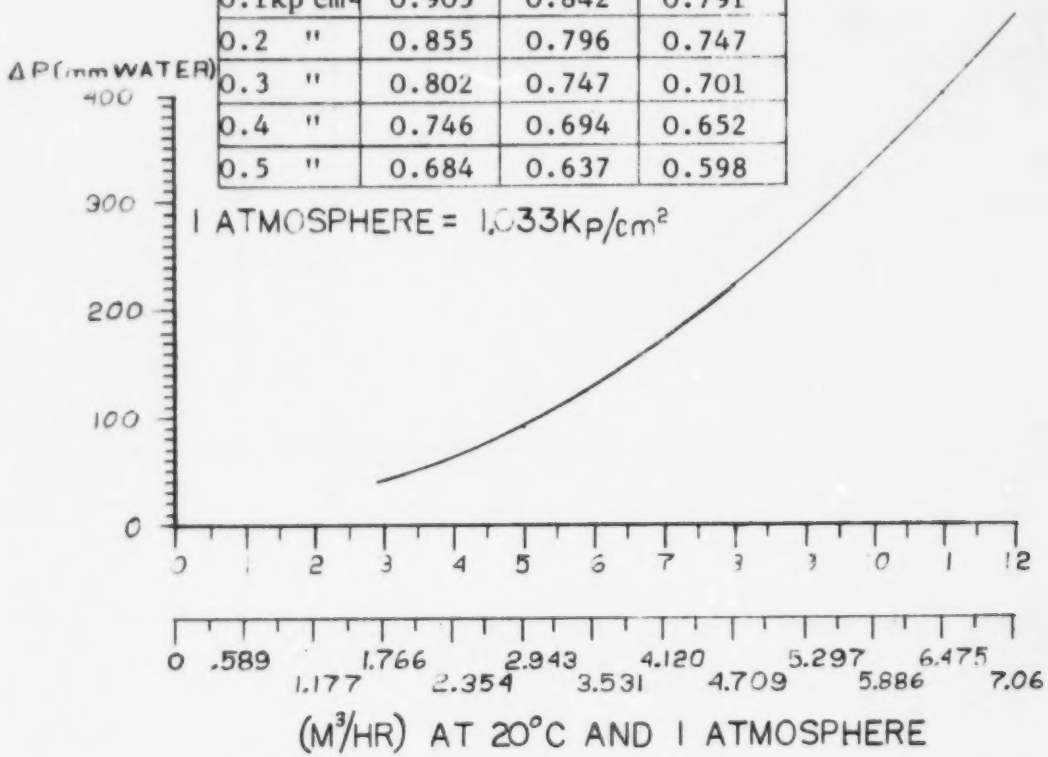


Figure A-3. Venturi flow meter calibration curve & correction factors.

6. The sample volume was calculated under estimated average venturi temperature and pressure conditions; Figure 3 was used to establish the required venturi pressure drop. The limit switches of the differential pressure controller were set a $\pm$ 20 mm from the established pressure drop.

7. A sampling sequence was performed and the initial and final gas temperatures and pressures were noted. The averaged values were used to re-calculate the required venturi pressure drop.

8. This calculation process was repeated until the pressure and temperatures at the venturi used in the calculations agreed with those obtained in the actual sampling cycle.

Output Format

The theoretical output is logarithmically related to particulate concentration. However the instrument output signal is not logarithmically transposed by the computer, making a manual transposition necessary. This is performed using Table 1 which relates instrument output to percentage of measuring range. Thus the concentration at a particular output is calculated as

$$C = XM \qquad \text{eqn. 5}$$

where C is dust concentrations in mg/M^3 at

1 atmosphere and 20^oC

X is percentage of measuring range obtained from

Table 1

M is measuring range in mg/M^3

Operation

In operation the instrument is fully automatic performing the following sequence of operations.

1. lower filter stage bellows, advance tape forward to locate, clean area between detector and source, close bellows.

2. for a period of 1 minute count, scale and record on one potentiometer the number of beta particles received by the detector. Nominal count rates in the range 15,000-20,000 cpm are used.

3. lower bellows, move tape back to locate same filter area in the filtration stage, close bellows.

TABLE A-1
% OF MEASURING RANGE FOR INDIVIDUAL RECORDER OUTPUTS
(LOGARITHMIC CONVERSION)

Recorder Output	% of Measuring Range	Recorder Output	% of Measuring Range
10	0.0	56	31.8
11	0.5	57	32.7
12	1.1	58	33.6
13	1.6	59	34.6
14	2.2	60	35.6
15	2.7	61	36.5
16	3.3	62	37.5
17	3.9	63	38.6
18	4.4	64	39.6
19	5.0	65	40.7
20	5.6	66	41.7
21	6.2	67	42.8
22	6.8	68	43.9
23	7.4	69	45.1
24	8.0	70	46.2
25	8.6	71	47.4
26	9.2	72	48.6
27	9.8	73	49.9
28	10.5	74	51.1
29	11.1	75	52.4
30	11.8	76	53.7
31	12.4	77	55.1
32	13.1	78	56.5
33	13.8	79	57.9
34	14.4	80	59.3
35	15.1	81	60.8
36	15.8	82	62.3
37	16.5	83	63.9
38	17.2	84	65.5
39	17.9	85	67.2
40	18.7	86	68.9
41	19.4	87	70.6
42	20.2	88	72.4
43	20.9	89	74.3
44	21.7	90	76.2
45	22.5	91	78.2
46	23.3	92	80.3
47	24.0	93	82.4
48	24.9	94	84.6
49	25.7	95	86.9
50	26.5	96	89.3
51	27.4	97	91.8
52	28.2	98	94.4
53	29.1	99	97.1
54	30.0	100	100.0
55	30.9		

4. open sample probe ball valve.

5. stop cam timer, operate pump and clock timer simultaneously. The differential pressure controller will operate the pump by-pass valve to maintain the venturi pressure within the set limits of ± 20 mm about desired and preset value.

6. the clock timer stops the pump and re-starts the cam timer.

7. the pump by-pass valve is returned to the fully open end-stop position, the sample probe valve is closed, the bellows are lowered and the tape advanced to bring the same filter area between the source and detector, the bellows are closed.

8. for a period of 1 minute, count, scale and record on the second potentiometer the beta particles received by the detector.

9. at the completion of counting, the ratio of the outputs of the two potentiometers is displayed on a strip chart recorder for a period of approximately 10 seconds.

10. the two potentiometers are re-set to zero and the sequence restarted as 1 above.

Calibration

Zero Check and Span

A zero check mode may be selected by switch function. In this mode the complete cycle of operation is performed except that the pump operation step is omitted, thus providing count data to the two potentiometers from the same area of clean filter. In the zero calibrate mode the output should be 10% of full scale. A maximum variation of ± 4% of full scale is allowed for the mean of ten sequential measurements provided that each individual measurement lies within ± 6% full scale of the mean value.

In the span check mode the complete cycle of operation is performed except that the pump operation step is omitted, and for the second beta count an absorber is physically interposed into a reproducible position between the source and detector. The absorber simulates a filter deposit and provides an arbitrary up-scale reading. The span check is used only as a check on operation and not as an upper range or linearity calibrate check. The instrument should always indicate the same value for the reference calibrate output with a maximum allowable variation of ± 4% of full scale for the mean of ten sequential measurements. Each individual measurement should lie within ± 6% of full scale of the mean value.

Gravimetric Calibration

Prime calibration is performed by comparison of beta and gravimetric measurements of collected filter deposits. Lengths of filter tape, cut to fit the calibrate filter holder, are dried and weighed. Deposits are collected on these filters by manually following the instrument sequence. The collected deposits and filters are re-dried and weighed. The weight gain measured gravimetrically is compared with that indicated by the instrument to provide a calibration of the beta system. It is stated by Lear Siegler Inc. that to obtain a calibration of the whole system, standard particulate sampling methods must be employed such as EPA Test Method 5, ASAE Performance Test Code 27 or ASTA D-2928-71. Such comparisons will allow the percent error introduced by moisture in the gas stream, sample collection, deposition in the probe and gas volume measurement inaccuracies to be evaluated with respect to the various reference techniques.

APPENDIX B

INSTRUMENT DESIGN AND OPERATION
MODEL 2414, AUTOMATIC STACK MONITOR
RESEARCH APPLIANCE CO.

GENERAL DESCRIPTION

The monitor system comprises nine major subsystems: (1) probe, (2) boundary layer diluter, (3) sample line, (4) sampling module, (5) heat exchanger, (6) dehydration module, (7) metering module, (8) control console, and (9) computer.

Probe

The probe is permanently installed in the stack location determined as optimum for representative sampling of the specific stack.

Boundary Layer Diluter

The boundary layer diluter is attached to the probe when a stack involves high levels of temperature, humidity, or particulate concentrations. This optional component conditions the effluent sample stream with dry instrument air (-40°F dew point) before it enters the sampling module.

Sample Line

This line connects between the Boundary Layer Diluter (if used) or probe and the sample inlet motorized ball valve in the sampling module. It is composed of stainless steel tubing with electrical heating element adjacent, surrounded with insulation and a weather jacket.

Sampling Module

This sealed, pressurized, stack-mounted unit includes a precision sampling nozzle (heated to 250°F), punched filter paper tape, beta radiation gauge, tape drive and photoelectric indexing mechanism, and storage provision for replacement tapes. It also has an integral heater that maintains temperature of 120°C in effluent sample inlet tube and nozzle to prevent condensation of entrained moisture. The sampling module case is pressurized

continuously with dry instrument air to maintain a controlled environment and assure optimum sampling accuracy.

The sampling nozzle shrouds and clamps the filter tape to produce uniform sample spots 1" in diameter. Each 100' length of tape will hold approx 600 individual samples. Replacement tapes are stored in the sampling case for proper conditioning prior to use.

Heat Exchanger

This unit, an aircooled fin-type heat exchanger, reduces temperature of effluent sample to approx 38°C or less - and partially condenses entrained moisture before the sample stream enters dehydration module.

Dehydration Module

This stack-mounted component, a refrigerated condenser/dryer, conditions the effluent sample stream to a 2°C dew point before it enters the metering module.

Metering Module

This subsystem contains 2 dry gas meters, 3 adjustable flow-measuring rotameters, 4 flow-control valves, a 14M^3/m free-flow vacuum pump, and a dryer for the instrument air used within the system.

One dry gas meter measures the volume of effluent sample that passes through system; the other measures volume of instrument air delivered to boundary layer diluter. The rotameters measure flow rates of (1) effluent sample stream, (2) dry air to diluter, and (3) dry air to purge or back-flush probe and diluter assembly. Flow rates are set by manually operated valves.

System design includes provision for periodic, automatic purging/back-flushing of effluent sample line in addition to probe assembly.

Control Console and Computer

The computer console controls all system sequences as well as individual component functions are regulated automatically by these two modules. The control console receives and assimilates input signals from the other sub-systems, then feeds them to the mini-computer for storage and subsequent calculation and print-out. Visual readouts are provided on master control's front panel for various relevant operating parameters, including indication of sequential phases. Instrumentation includes an electronic timer that controls timing intervals for beta gauging, a digital beta impulse counter, and an add-subtract volume counter.

The add-subtract volume counter adds sample volume flow, on a cumulative basis, and automatically subtracts from it the volume of dilution air introduced into the sample stream.

The mini-computer is operated by magnetic punched-card program.

Pre-Operational Set-Up

The total sample volume is determined as the difference in readings of the two gas meters. One measures dilution air while the second measures total sample plus dilution air under dry conditions. The average gas meter temperatures and stack gas temperature, humidity and velocity must be measured prior to using the equipment for dust loading measurements. The nozzle size must be selected together with the sample volume flow rate to provide near isokinetic sampling under most stack gas conditions. Since the filter impedance will increase as a deposit is accumulated, the sample flow rate will decrease necessitating selection of an average sampling rate. The dilutor air flow rate should be adjusted to approximately 50% of this average sample flow rate and the sample time selected to give a beta count of the filter plus deposit approximately 50% of that on the clean filter.

The computer must be programmed using the magnetic program cards provided. The following six factors must be manually loaded into the program.

1. set decimal point to 2
2. set the constant to provide the output dust loading in the required units.
3. set sampling time
4. set counting time
5. set the time delay between sampling cycles
6. set the alarm level

Output Format

The computer system provides all time, function and calculation capabilities. The output is printed on tape as the following sequence of numbers for each sample

Number of beta particles counted on clean filter
Volume of gas sampled, cubic feet
Number of beta particles counted on filter with deposit
Calculated particulate emission rate mg/M^3

A preset alarm level may be included which, if exceeded, causes the printed emission rate to be preceeded and followed by a row of dots.

Operation

The entire operation of the monitor is controlled by the program sequencer.

In step one the sequence programmer sends a signal to the tape drive right motor. The motor is controlled by a triac. As soon as the index hole on the filter tape passes away from the optical index reader the programmer is placed in a stop mode. The programmer will remain in step 1 until the next index hole passes into the optical index reader.

At this point the programmer will immediately jump to step two. In step two the Beta Count Timer is triggered on. The Beta Count Timer starts the Beta Counter and also places the sequence programmer in the stop mode for the duration of time set on the Beta Count Timer. At the end of this counting time the sequence programmer will jump to step three thereby stopping further beta counting.

Steps 3, 4, 5, 6, 7 are data enter steps. During these steps the beta count on the Beta Counter is entered into the computer.

Step 8 resets the Beta Counter to zero and resumes the calculation in the computer.

Step 9 is a drive tape left command, a reset command for the sample volume counter, and a command to activate the tape out alarm system. If in this step the tape does not index properly (the index hole on the filter tape does not move out of the optical index reader) the control console will go into "tape out alarm". In this mode a sharp, high pitch sound will be heard, the "Tape Out" lamp will be lighted. To reset the system, place computer on "stand by", place tape load switch, in Sampling Module, in the load position (this lifts nozzle) and load fresh tape (or repair break in the tape) made sure tape hole is under optical index reader. After tape is loaded, place tape load switch in normal position and move computer switch from stand by to "on" position, push "Tape Out" indicator in and light will go out. Depress start switch on computer, sampling sequence will now automatically begin.

Step 10 is the sampling mode for the instrument and the sampling pump should be one. Sampling will occur for the preselected time. At this point the programmer will jump to step 11.

Steps 11 - 18 are a repeat of steps 1 - 8.

Steps 19 - 20 are not used on a single stack monitor. On a two stack monitor step 19 is used to switch the system from one stack to the other.

Calibration

Prime calibration is performed by comparison of beta and gravimetric measurements of collected filter deposits. Lengths of filter tape are dried and weighed. Deposits are collected on these filters by manually following the instrument sequence. The collected deposits and filters are re-dried and weighed. The weight gain measured gravimetrically is compared with that indicated by the instrument to provide a calibration of the system.

APPENDIX C

DESCRIPTION OF THE PARTICULATE REFERENCE METHOD USING THE EPA SAMPLING TRAIN

GENERAL PRINCIPLE OF OPERATION

The instrument is designed to permit isokinetic extraction of a stack-gas sample, to filter the particulate material, to condense and remove the moisture and to measure the total gas flow. The instrumentation and its use is described in detail in Reference 1.

Instrument Design and Operation

The instrument is shown schematically in Figure 1-2 to comprise the following modules.

1. Probe assembly including the sample nozzle and heated probe, S type pitot tube, stack gas temperature measuring system and the sample probe temperature measuring system.

2. Particle catchment comprising a cyclone and fiber glass filter system in an oven capable of being heated above the stack gas dew point.

3. Impinger train comprising a modified Greenberg-Smith impinger containing water, a Greenberg-Smith impinger containing water, an empty modified Greenberg-Smith and one containing silica gel. All impingers are immersed in an ice bath.

4. Control box connected to the sampling box by flexible connections. The control box contains a dry gas meter, orifice meter, pump, manometers for monitoring pitot tube and orifice meter differential pressures, and general control functions.

In operation particulate samples are withdrawn isokinetically from the stack at preselected points. Isokinetic sampling velocity is obtained by matching the stack gas velocity as measured by pitot tube and the volume flow rate as measured using the orifice meter. Suitable adjustments are made for stack gas humidity and composition, nozzle area and stack gas and orifice temperature and pressure. These procedures are performed using a standard nomograph relating operational parameters to the pressure drop needed to be developed across the orifice meter for isokinetic sampling.

Samples were collected in the heated cyclone and on the fiber glass filter for gravimetric measurement. Material collected on the probe walls was removed by washing and brushing and was collected and weighed. Moisture condensed in the impingers was

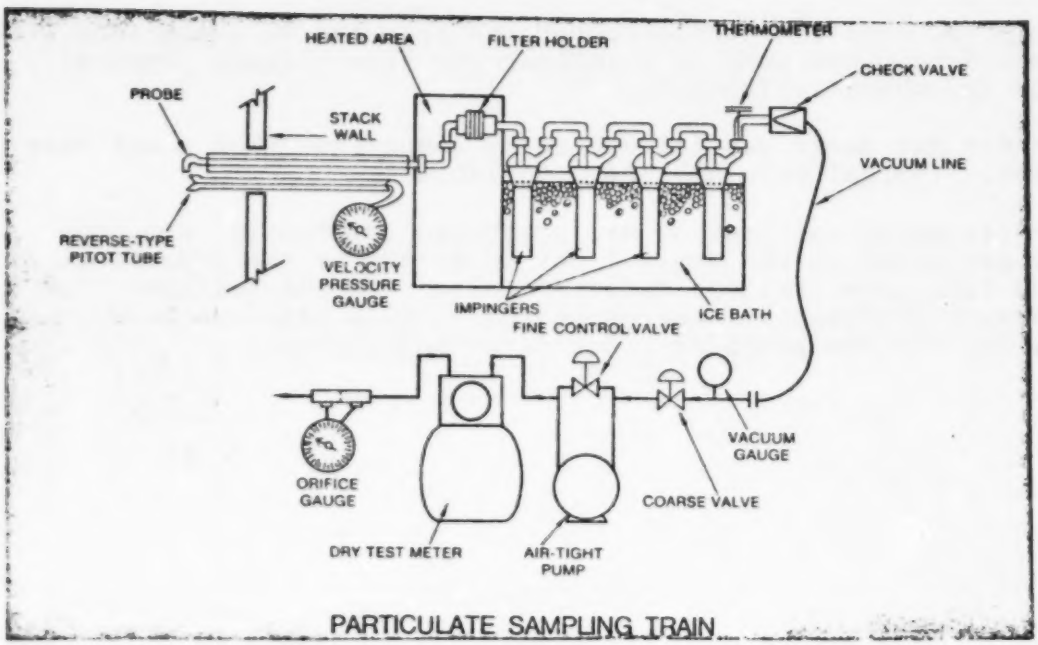


Figure A-4. Particulate sampling train

determined by volumetric measurement, while moisture absorbed in the silica gel was determined gravimetrically.

A typical data sheet and summary of calculations are shown in Tables 1 and 2.

Calibration

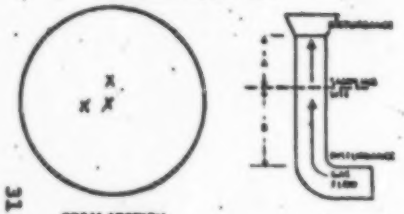
The pitot tube correction factor was measured by comparison with a standard pitot tube in a laminar air flow stream. Typical data are shown in Table 3.

The dry gas meter was calibrated by comparison with a wet test meter. Typical data are shown in Table 4.

Orifice meter calibration was performed internally using the dry gas meter in the control box to determine the dependence of flow rate upon pressure differential across the orifice. The pressure differential corresponding to 0.75 scfm was used in setting the nomograph for isokinetic adjustment.

PARTICULATE FIELD DATA

SCHEMATIC OF STACK



CROSS SECTION

PLANT Ferrite Calciner
DATE 1/24/74
LOCATION Burrwick 6
OPERATOR LG
STACK NO. 1 Calciner
RUN NO. 2
SAMPLE BOX NO. SGB
METER BOX NO. SGB

AMBIENT TEMPERATURE 28°
BAROMETRIC PRESSURE 30
ASSUMED MOISTURE, % 25
PROBE LENGTH, in. 72
NOZZLE DIAMETER, in. ½
STACK DIAMETER, in. 23½
PROBE HEATER SETTING 300
HEATER BOX SETTING 300

METER ΔH 1.6
C FACTOR .58
PROCESS WEIGHT RATE

Filter Clean .7310
Filter Dirty .8845
Probe Washings .0492
Total Collected .1977

TRAVERSE POINT NUMBER	SAMPLING TIME (θ), min.	STATIC PRESSURE (in. H_2O)	STACK TEMPERATURE (T_s), °F	VELOCITY HEAD (ΔP_s)	($\sqrt{\Delta P_s}$)	PRESSURE DIFFERENTIAL ACROSS ORIFICE METER (ΔH) in. H_2O ACTUAL	DESIRED	GAS SAMPLE VOLUME (V_m), ft³	GAS SAMPLE TEMPERATURE AT DRY GAS METER: INLET ($T_{m_{in}}$), °F	OUTLET ($T_{m_{out}}$), °F	SAMPLE BOX TEMPERATURE °F	TEMPERATURE OF GAS LEAVING CONDENSER OR LAST IMPINGER °F	PUMP VACUUM in. Hg gauge	VELOCITY fps
1	5	.12	660	.03	.173	.54		330.200		26	230	34		
2	5	.12	680	.03	.173	.55				27	240	34		
3	5	.13	680	.03	.173	.55				28	280	32		
4	5	.13	680	.03	.173	.55				29	300	35		
5	5	.12	680	.03	.173	.55				28	290	34		
6	5	.12	680	.03	.173	.55				26	300	34		
7	5	.13	680	.03	.173	.55				28	300	35		
8	5	.13	680	.03	.173	.55			40	29	305	36		
9	5	.13	680	.03	.173	.55			42	31	310	36		
10	5	.13	680	.03	.173	.55			42	30	305	37		
11	5	.13	680	.03	.173	.55			43	31	300	38		
12	5	.12	680	.03	.173	.55		355.101	44	32	300	38		
TOTAL	60							24.901						
AVERAGE			680	☒	.173			24.403						13.81

TABLE

	VOLUME OF LIQUID WATER COLLECTED	IMPINGER VOLUME ml	SILICA GEL WEIGHT, g
FINAL	189 12.3	208.4	
INITIAL	180 280.0	200	
LIQUID COLLECTED	89 12.3	8.4	

ORSAT MEASUREMENT

	TIME	CO_2	O_2	CO	N_2
1					
2					
3					

COMMENTS:

SOURCE: Site 1 **PDL PROJECT NO:**

TEST NUMBER: 1/24/74 Run 2

	ENGLISH UNITS (29.92in. 70°F)	CONVERSION FACTOR	METRIC UNITS (760mm 20°C)

Volume of sample at standard conditions, dry basis

$$V_{mstd} = \left[17.71 \frac{°R}{in.Hg}\right] V_m \left[\frac{P_{bar} + \frac{\Delta H}{13.6}}{T_m}\right]$$

= 24.46 cu.ft. x 0.02821 .6901 M^3

Volume water vapor in sample at standard conditions

$$V_{wstd} = \left[0.0474 \frac{cu.ft.}{ml}\right] V_{lc}$$

= 5.328 cu.ft. x 0.02821 .1503 M^3

Moisture content in stack gas

$$B_{wo} = \frac{V_{wstd}}{V_{mstd} + V_{wstd}}$$

= 17.89% 17.89%

Particle concentration in stack gas on dry basis

$$c'_s = \left[0.01543 \frac{gr}{mg}\right]\left[\frac{M_n}{V_{mstd}}\right]$$

= .1247 grains/scf x 2297 286.5 mg/M^3

$$= 2.205\ 10^{-6} \frac{M_n}{V_{mstd}}$$

$= 17.82 \times 10^{-6}$ lbs/scf

Stack gas volume flow rate on dry basis

$$Q_s = 3600^{.8211} (1-B_{wo})\ V_s A \left[\frac{T_{std.}\ P_s}{(T_s)_{avg} P_{std}}\right]$$

$= 5.181 \times 10^4$ scfh x 0.02821 1641 M^3/hr

(A = 3.021 sq.ft. V_s = 13.81 fps)

Process rate or BTU rating P_W = _____ _____

Emission Rate

$Q_s\ c'_s$ = 1.037 lbs/hr. x 0.4536 .4703 kg/hr

$\frac{Q_s\ c'_s}{P_W}$ = _____ lbs/ x 0.4536 _____ kg/

$$I = \frac{(1.667 \frac{min}{sec})\ T_s \left[\frac{(0.00267 \frac{in.Hg.cu.ft.}{ml\ °R}) V_{lc} + \frac{V_m}{T_m}(P_{bar} + \frac{\Delta H}{13.6})}{\theta V_s P_s A_n}\right]}$$

(A_n = sq.ft.) = 92.59 % 92.59 %

TABLE A-3

EQUIPMENT CALIBRATION DATA
PITOT TUBE

STANDARD TYPE PITOT TUBE

Assume CF = 1.0
Air temperature = 68°F

P	Vel:fps
0.33	38.3
0.10	21.1

S TYPE PITOT TUBE

P	CF:Calculated
0.50	0.8128
0.15	0.8176
Av.	0.8152

Calibration date: 12/18/73

TABLE A-4

EQUIPMENT CALIBRATION DATA
DRY GAS METER

Final	Initial	Difference	P "WG	Temp °F	Final	Initial	Difference	H	°F
2.100	0.900	1.100	0.55	77.9	21.122	20.00	1.122	0.1	74
3.212	2.100	1.110	0.50	78.0	23.262	22.122	1.140	0.1	74
4.229	3.212	1.017	1.1	77.8	24.291	23.262	1.029	0.3	74
5.491	4.425	1.066	1.5	77.8	25.386	24.300	1.086	0.5	75
6.571	5.491	1.080	2.0	77.5	26.486	25.386	1.100	0.75	76
7.565	6.571	0.994	2.6	77.5	27.503	26.486	1.017	1.00	76
	Av.	6.367				Av.	6.494		

APPENDIX D

Statistical Analysis

The following statistical analysis was performed to evaluate the data for Site 1. Identical analytical procedures were followed for Sites 2 and 3.

Let P(t) be the particle loading of the stack at time t at the orifice expressed in gm/M^3 dry basis. Let R(t) be the flow rate expressed in M^3/sec dry basis. Then P(t)r(t) is the particulate concentration expressed in gm/sec at the orifice. The manual instrument measurement at time t_o is $x(t_o)$ expressed in gm/M^3. It is given by

$$X(t_o) = \frac{\int_{t_o}^{t_o + 1\ hr} P(t)\ r(t)\ dt}{\int_{t_o}^{t_o + 1\ hr} r(t)\ dt}$$

The Argos 1 Beta Gauge takes its sample for only 43 seconds but takes a similar measurement. We assume that r(t) the emission rate of the stack, over the one hour span is given by

$$r(t) = r_o + \xi(t)$$

where r_o is a fixed rate and $\xi(t)$ is a random variable such that for each t, the mean is 0 and the variance is $\sigma^2_{\xi}(t)$.

The beta gauge takes measurements at four minute intervals. We denote these by

$$Y(t_o) = \frac{\int_{t_o}^{t_o + 43\ seconds} P(t)\ r(t)\ dt}{\int_{t_o}^{t_o + 43\ seconds} r(t)\ dt}$$

To make this data compatible with that of the manual instrument, we can write

$$\frac{\sum_{k=1}^{15} \int_{t_k}^{t_k + 4\ \text{min}} P(t)\, r(t)\, dt}{\sum_{k=1}^{15} \int_{t_k}^{t_k + 4\ \text{min}} r(t)\, dt}$$

Where t_k is the kth four minute interval during the hour. The estimate, which was used, for any k of $\int_{t_k}^{t_k + 4\ \text{min}} P(t)r(t)dt$ is $4 \int_{t_k}^{t_k + 43\ \text{seconds}} P(t)r(t)dt$. Hence, we estimated the numerator by

$$4 \sum_{k=1}^{15} \int_{t_k}^{t_k + 43\ \text{seconds}} P(t)\, r(t)\, dt$$

In addition from our assumed model, the expected value for any k of

$$\int_{t_k}^{t_k + 43\ \text{seconds}} r(t)dt = 1/83.7(r_o)$$

Using these we have

$$X(t_o) = \frac{\int_{t_o}^{t_o + 1\ \text{hr}} P(t)\, r(t)\, dt}{\int_{t_o}^{t_o + 1\ \text{hr}} r(t)\, dt} = \frac{\sum_{k=1}^{15} \int_{t_k}^{t_k + 4\ \text{min}} P(t)\, r(t)\, dt}{\sum_{k=1}^{15} \int_{t_k}^{t_k + 4\ \text{min}} r(t)\, dt}$$

$$= 5.6\ \frac{\sum_{k=1}^{15} \int_{t_k}^{t_k + 43\ \text{seconds}} P(t)\, r(t)\, dt}{15(1/15\ r_o)}$$

$$= \frac{1}{15} \quad \frac{\sum_{k=1}^{15} \int_{t_k}^{t_k + 43 \text{ seconds}} P(t)\, r(t)\, dt}{r_o/83.7}$$

$$= \frac{1}{15} \quad \sum_{k=1}^{15} \left(\frac{\int_{t_k}^{t_k + 43 \text{ seconds}} P(t)\, r(t)\, dt}{\int_{t_k}^{t_k + 43 \text{ seconds}} r(t)\, dt} \right)$$

This latter is the average of the 15 observations from the beta gauge taken at four minute intervals. Performance criteria used were relative accuracy, calibration error, instantaneous drift and long term drift.

Relative accuracy is defined as the difference between the measurement system and the reference system outputs expressed as a percentage of the reference value. Calibration error is defined as the difference between the measurement system reading and the exact concentration of material on a calibration filter, expressed as a percentage of the measurement system reading. Instantaneous drift is defined as the drift in the system between successive readings taken with no time lag between readings. It is expressed in terms of 95% confidence intervals in full scale deflection. Long term drift is defined as the drift in the system between readings of the system taken 24 hours apart. It is expressed in terms of 95% confidence intervals of full scale detection.